Improving Cable Logging Operations for New Zealand's Steep Terrain Forest Plantations

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Abstract

Cable logging will become more important as harvesting shifts to greater annual proportions on steep terrain in New Zealand. The costs of cable logging are considerably higher than that of conventional ground-based methods. Improving cost-effectiveness has been identified as key to ensuring the forestry industry remains cost competitive in the international market. This thesis focuses on ways to better understand and improve cable logging methods by specifically focusing on rigging configurations. The investigation was conducted through a comprehensive literature review, an industry survey to establish current use and preferences, a Delphi survey with experts to establish actual advantages and disadvantages, scale model testing to establish some fundamental knowledge of tension to deflection relationship, and finally a series of targeted case studies to establish both productivity and skyline tension in actual operations. Each of these aspects of the research topic employed different methodology.

The literature review highlighted the most relevant research relating to cable logging world-wide spanning nearly a century. Various research papers, manuals, books and computer software were summarized. While many aspects of cable yarding operations have been investigated, much of it focusing on various aspects of operational efficiency through case studies, there is very limited information with regard to rigging configurations. The survey of 50 cable logging practitioners determined what rigging configurations were commonly used in New Zealand. It includes their perceived advantages and disadvantages for varying levels of deflection, but also for specific scenarios such as pulling away from native forest boundaries and flying logs over a stream. Results showed that there were many conflicting perceptions about rigging configuration options.

Using an expert panel, a Delphi process was used to derive consensus on what advantages were truly unique to each configuration. This allowed the longer lists of perceived advantages from the industry survey to be pared down to a concise list of ad/disadvantages that will be used in the updating of the Best Practice Guidelines for Cable Logging.

To increase our fundamental understanding of tension / payload / deflection relationships, an experiment was conducted in a controlled environment. Using a model yarder in a lab and continuous tension and video recording devices, the dynamic skyline behavior of three similar configurations were tested: North Bend, South Bend and Block in the Bight. The tensions were compared by use of a two-way analysis of variance, which indicated configuration and choker length were significant variables in some but not all of the dynamic load tests. Results also showed that some configurations performed better than others in minimizing the shock loads due to dropping into full suspension, impact with ground objects, and breakout during bridling.

Finally, a series of eight studies were conducted on targeted logging operations where relevant stand and terrain parameters were related to the continuous skyline tension monitoring, and recording of productivity through time study. The three targeted configurations included (1) North Bend, (2) Standing skyline using a motorized slack-pulling carriage and (3) a live skyline using a motorized grapple carriage.

Results showed that peak and average tensions, as well as amplification factors and the payload to tension relationship, varied between configurations. The study also showed that tensions could be collected to compute measures of payload and tension efficiency, which provided insight into operational performance. The safe working load was exceeded in 53%

of all cycles studied and across seven of eight study sites and 14 of 16 spans. Cycle times were significantly different between rigging configurations and that production information could be used to compute measures of labor and energy consumption as well as payload and tension efficiency; which also provide insight into operational performance.

The industry should give serious consideration to the use of tension monitors. Tension monitors have many benefits and have the potential to improve cable logging operations in New Zealand. Monitoring tensions can help one learn new techniques or methods (i.e. rigging configurations), help improve payload analysis software for future planning and help evaluate new technology and machinery.

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Conference Presentations

Harrill H. and R. Visser. What is the best rigging configuration to use in New Zealand cable logging operations? 34th Council on Forest Engineering (COFE). June 12-15, 2011, Quebec City, Canada.

Harrill, H. 2012. Which rigging configurations are used in New Zealand cable logging operations? New Zealand Institute of Forestry (NZIF) Annual Conference. Poster. Christchurch, New Zealand.

Harrill, H. 2012. Which rigging configurations are used in New Zealand cable logging operations? Council on Forest Engineering (COFE). Poster. New Bern, North Carolina, USA.

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Visser, R., D. Hopper, J. Simmonds, M. Wakelin, H. Harrill. 2013. Efficiency of log vessel loading operations: A loader configuration case study. 2013 Missoula, Montana, USA.

Future Forest Research (FFR) Members Meeting

2011 March Rotorua, August Wellington

2012 March Gisborne, August Rotorua

2013 September, Blenheim

FFR Technotes

Harrill, H., and R. Visser. 2011. Rigging configurations used in New Zealand cable logging. Future Forests Research Ltd. (FFR). HTN03-11. 6.

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FFR Reports

Evanson, T., D. Amishev, R. Parker, H. Harrill. An evaluation of a ClimbMAX steep slope harvester in Maungataniwha forest. Future Forest Research Ltd. (FFR). Research Report H013. 15.

Workshops

Co-hosted Forest Industry Contractors Association (FICA) 2012 Cable Logging Workshops

- 20th April, Nelson
- 27th July, Tokoroa
- 29th November, Balclutha

University of Canterbury Teaching Experiences

Courses Taught:

- 2011-2013 Foundations of Engineering Lab Tutorial (ENGR 101)
- 2014 Introduction to Forest Engineering (FORE 205)

Teaching Assistant & Guest Lecturer:

- 2011-2013 Introduction to Forest Engineering (FORE 205)
- 2011-2014 Forest Harvest Planning (FORE 422)
- 2011-2014 Forest Transportation and Road Design (FORE 423)
- 2014 Environmental Forestry (FORE 445)

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Chapter 1: Introduction

1.1 Background

1.1.1 Forestry & Forest Operations

Forests are one type of natural resource which exists on earth. Forestry is the art and science of managing the forest resource to produce goods and services. Forestry's inputs by human interaction to achieve these goods and services, at the desired time, place and form; are known as forest operations (Sundberg and Silversides 1987). The types of operations and when they are required are determined by the resource, what goods and services are desired, and economics.

Forests which are managed for producing goods and services are grown in cycles of time (years), with different operations taking place at different periods in the cycle. The types of operations vary greatly by resource, product, and enterprise, but generally consist of planting, silviculture, harvesting (i.e. logging), transportation, and processing. Together, these operations form a dynamic and complex forest production model (Sundberg and Silversides 1987). Harvesting is a forest operation which alone represents a complex part of the overall production model; due to the wide variety of machines and techniques available. Common harvesting operations can be classified into two broad categories of logging systems, based on the method of extraction from stump to roadside and the slope of the terrain: ground-based (<40% slope) and cable logging (>40% slope) (Studier and Binkley 1974). A third broad category is 'aerial', which are typically helicopter logging operations and due to their high costs, are used in areas where access is restricted.

There are many different cable logging systems that have been developed over the years in different countries. They are composed of different machines, tools and methods available, each with their own requirements and capabilities. These culminate in a very large number of different combinations, whereby texts and manuals such as Studier and Binkley (1974) or Liley (1983) can provide a good overview. Therefore, choosing the right one which is most suited to produce the desired goods and services, considering the characteristic of the resource and the goals of the enterprise, is difficult. The problem of which logging system to choose and how best to implement them created the need for a forest engineer; a specialist with skills in engineering, analysis, and optimization who became involved in systems planning (Samset 1985).

1.1.2 Forestry in New Zealand

When European settlers first arrived in New Zealand in the mid 1800's, much of the country was still covered in native forests. Many of these forests were cleared and burned by the early settlers for grazing of sheep and cattle. Native deforestation was so rapid that by the early 1900's some tree species were threatened with extinction. In 1918 exports of native timber were restricted, and in 1925 the government introduced financial incentives to create plantations of exotic species to reduce the pressure on native forests. *Pinus radiata* seed was previously imported from California in the 1840s to form wind breaks on farms. The species proved to grow faster in New Zealand than in its native range, and soon became the species of choice for reforestation. Mass plantings in the 1920's 1930's and 1960's, created the exotic plantation forestry industry that still exists today, with trees grown in 30 year rotations (NZFOA 2014).

Today, forests cover 31% of New Zealand's land, about 24% of which is native forest and 7% is plantation forests of which just over 90% is *Pinus radiata*. The net stocked plantation forest area is 1.72 million hectares, with an average annual harvest of 44,100 hectares (NZFOA 2014). The average tree size is around 2 m^3, and the average volume per hectare is 535 m^3, which equated to a record 26 million cubic meters harvested in 2013 (NZFOA 2013). The forestry sector has prospered in the last five years with the high log prices due to increased demand from China; generating 4.5 billion dollars in export revenue and was the country's third largest export earner in 2013. Increased plantings in the 1990's due to high log prices increased the net stocked area, in that age class. The 1990's plantings have started to reach maturity and will be harvested in the next 10 years with increased harvest volumes annually in what is referred to as the "wall of wood," (Figure 1.1).

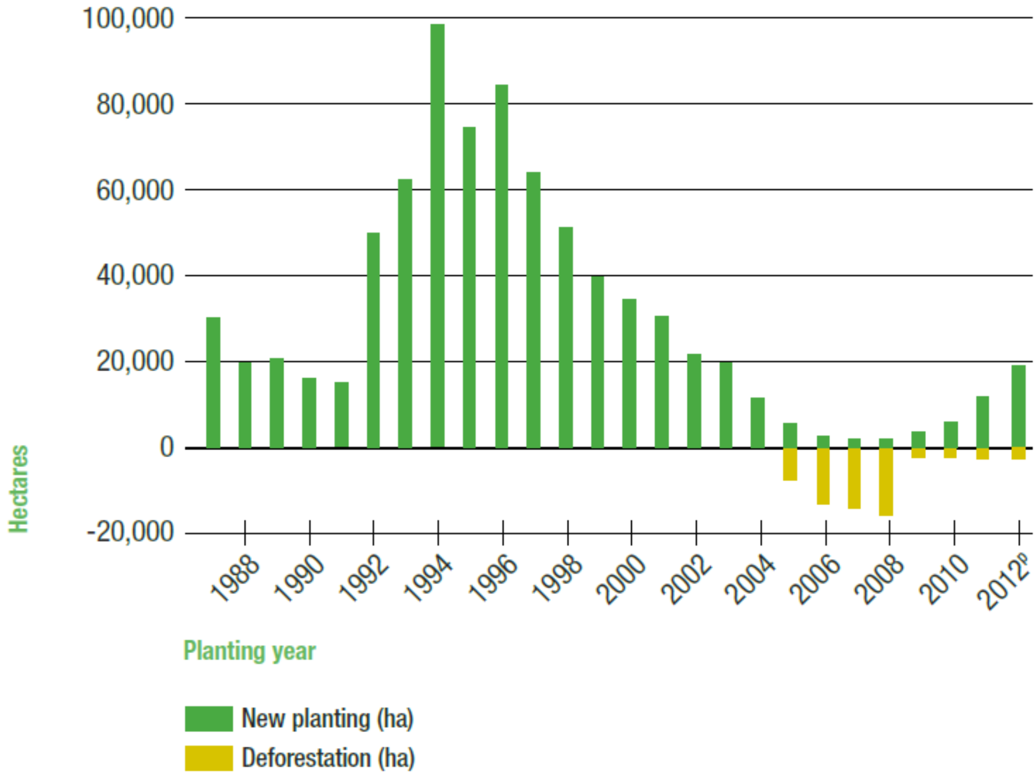

Figure 1.1: New Zealand's exotic forest plantings by year and net stocked area (NZFOA, 2013).

1.1.3 The need for improvement in cable logging

The industry has recognized that harvesting the "wall of wood" will not be an easy task as many of these forests were planted on steep ground and/or remote areas with little infrastructure (Raymond 2012). With increased global competition in supplying logs the industry faces the challenge of remaining profitable. The costs of harvesting on steep terrain are on average 40% more than harvesting on flat terrain (Visser 2014). Additionally, New Zealand will require more forest workers and machines to harvest the increasing annual volumes. A survey by (Visser 2013) found that on average two cable yarders a month were being imported to New Zealand, and each of these machines requires a crew of eight people on average.

The New Zealand forestry sector, supported by the New Zealand Government, has identified improving cost-effectiveness of steep country harvesting as key to ensuring greater profitability in forestry. Steep country forests already contribute more than 40% of New Zealand’s annual log harvest, and this is forecast to rise to over 60% in coming years (FFR 2010). Harvesting and transport costs are typically 40-60% of the delivered costs of logs, yet little research has been conducted in this area in New Zealand since the late 1990s when the former Logging Industry Research Organization (LIRO) was disestablished. Present harvesting methods on this terrain, such as cable logging, have changed little in 50 years (FFR 2010). Depending on factors such as small payloads, high fuel consumption, poor communication and organization, slope, and adverse weather, these operations can be costly and hazardous to workers on the ground (Amishev 2011; Slappendel et al. 1993). If New Zealand is to remain competitive in international log markets, then improvements in cable logging operations in terms of production and safety will be necessary. The current goal of the industry should be to improve profitability by decreasing costs and increasing productivity (FFR 2010).

1.1.4 Planning Forest Operations

“Planning is the most essential function to be performed in a logging business. It’s essential because it provides the discipline that welds together all parts of the harvesting system, identifying and resolving conflicts, recognizing constraints, and providing for an orderly

input of resources. Without a plan or with an inadequate plan, the result is waste, underutilization of productive resources and excessive cost (Conway 1982).”

Effective planning incorporates the land owner’s objectives (i.e. fiber supply and forest regeneration) while also considering social and political objectives (i.e. preservation of environment and alternative forest uses). The corporate, social and political objectives provide direction towards a harvest system but, there are also objectives for the harvesting system itself.

Heinimann (2000) outlined the criteria for success in a modern forest harvesting operation as follows:

1. Physically capable: The harvest system or method (i.e. rigging configuration) selected must be physically capable of accomplishing silvicultural and resource management objectives including safety practices.
2. Economical: The harvest system or method selected must be economically efficient and feasible to obtain a net profit.
3. Environmentally acceptable: The harvest system selected must meet environmental requirements/laws and should aim to minimize impacts.
4. Socially acceptable: The harvest system selected must be socially acceptable including labor regulations and best management practices.

Throughout the course of history, logging operations and associated personnel have been primarily concerned with whether a harvesting system is physically capable and then whether it’s economically efficient. Only in the later part of the 20th century have social and environmental acceptability been considered to the extent they are today. Primarily due to the environmental movement in the USA of the 1970’s and increased public awareness and participation in management of natural resources on public land. However, economics still play an important role in planning and decision making especially when harvesting timber on steep terrain with cable yarders.

The costs of cable logging on steep terrain are considerably higher the cost of conventional flat-country logging. Costs include the capital investment in machinery (fixed costs), the variable operating and repair costs and the cost of labor. Half of these costs are contributed by the by the yarder, and therefore production is of paramount importance (Murphy 1979). Production is affected by the size of the trees, the total volume, method of felling and yarding as well as various other factors. However, there has been a general trend internationally where the increase in labor costs has outpaced the increase in machine costs (fixed + variable). For instance, Samset (1985) found that labor costs in Norway were 16 times greater in 1980 compared to 1950, while the consumer price index was only five times greater than it was in 1950. During this period there was an international trend to replace forest workers with new specialized forest machinery, which were not only more productive but also becoming more cost competitive. The author also noted that despite the considerable development in cable logging systems, the increase in productivity had not kept up with the increase in inflation during the same period, and the relationship between costs and productivity of older more labor intensive systems in 1962 were almost the same as more capital intensive systems used in 1975. Still the focus of much logging and cable logging research has been in the area of increasing production, with the intention of decreasing unit production costs ($/tonne).

The approach of treating logging as a cost center rather than a profit center originated when logging was part of an overall operation to supply timber and was common to many vertically integrated companies (Stuart 2003; Stuart et al. 2010). Logging was viewed as a component that reduced stumpage rates for the land owner. Therefore, traditional economic analysis focused on quantifying and reducing costs to improve overall profitability. There are two problems associated with the previous approach: First the general trend in the business environment, and the second in how fixed costs are defined. Most of the large vertically integrated forest management companies in the USA and New Zealand have split up their ownership, and logging is now more commonly being performed by a small independent contractor who operates as a for profit business rather than a cost center; which is a conflict in goals (Baker and Greene 2008; Stuart et al. 2010). The reason many believe increasing production is good is because literature on costs over the years suggest it's more efficient. The traditional assumption has been that the majority of logging costs such as depreciation, taxes and insurance continue to be fixed, and therefore can be reduced, on a per unit basis ($/tonne) by increasing production (tons); (Carter and Cubbage 1994; Stuart et al. 2010). Stuart et al. (2010) found that equipment costs (including interest, insurance and taxes) were more variable than fixed, with the percentage of expenditures ranging from 3% to 38% for the same contractor within the period of one year. The authors determined that there are fixed costs in logging, but only for short periods of time (i.e. weeks and days). Therefore, fixed costs can be diluted by increased production but only over that same time period. The authors conclude that making business decisions based the potential dilution of fixed costs through increased production is risky, because it is difficult to predict annual production and the structure of a firm's costs and revenues over long periods of time. Despite this Drolet and LeBel (2010) found that logging contractors organizational and entrepreneurial performance remains one-dimensional, focused on production, where production was most often used by contractors as their best performance indicator.

Much of the forest industry's obsession into increased production is central to the theory of economies of scale, where increasing production leads to increasing returns to scale. Literature on returns to scale has been limited in forestry and differed in their main findings. Carter and Cubbage (1994) and Bauch et al. (2007) found increasing returns to scale in forest harvesting operations, while others have found decreasing returns to scale (Baker and Greene 2008; LeBel and Stuart 1998; Stuart et al. 2010). Results from the later studies suggest that for some logging contractors, after reaching a certain scale, it will become increasingly difficult to maintain profitability through solely increasing production. LeBel and Stuart (1998) found that for a given scale contractors with greater efficiency always have lower costs compared to the less efficient. However, how one defines efficiency is dictated by how they define their problem.

1.1.5 What is Efficiency?

All problems in life come to surface with conflicting demands in resources, time or space; in the case of the forest industry in New Zealand the problem is, how to increase production and decrease costs to improve profitability. Worrel (1959) said the basic economic problem in forestry is to achieve the most efficient use of productive resources. The problem exists because either some fixed amount of output is desired or; a limited amount of one or more productive factors is available. However, the differing reasons for why the problem exists lead to very different views on what it means to be economically efficient. The difference in views can be explained by the two classical forms of forestry; "exploitative" versus “sustained yield.” (Sundberg and Silversides 1987). The difference is that in sustained yield forestry, the limiting factor is the forest resource itself; while in exploitative forestry the forest is assumed to be unlimited and the limiting factor manifests somewhere else (i.e. markets, capital or labor). Exploitative forestry views efficiency as maximizing profit per unit of production. When the forest resource is in shortage, as in sustained yield forestry, efficiency is to maximize profit per unit area. In exploitative forestry one such limiting factor may persist at a certain time or stage and then may change to another. When all the shortages are in sufficient supply the forest resource itself become the shortage and the form of forestry changes from exploitative to sustained yield. From this perspective forestry starts in all nations as exploitative and eventually changes to sustained yield, but this has not happened yet with exception to perhaps Western Europe.

Regardless of or how one defines their problem and hence their definition of efficiency, the international trend and interest in forest harvesting research, technology and machine developments has been to increase efficiency. This in turn, has led to some interesting innovations which were unique to their region and what was considered efficient. Research should continue to quantify these effects (particularly in short-rotation stands) and to develop ways of achieving greater efficiency (Murphy 1979).

Cavalli (2012) found that the last 10 years of research by forest engineers interested in cable logging was directed mainly (45%) towards efficiency. Efficiency can most simply be defined as a ratio of total inputs used to total outputs produced. One definition of business is that it’s the survival of the least inefficient (Silversides 1975). This could also be said about the business of forest harvesting operations. In the early 1920’s efficiency was first applied to forestry with the introduction of the concept of “control,” adopted from industrial engineering processes by the Abitibi Power and Paper Co Ltd in Canada (Silversides and Sundberg 1987). Control had two meanings when introduced at the time: the act of controlling, restraining or directing influence (i.e. regulating), and it also meant a standard of comparison to check the results of action against. In any case, practitioners were trying to benchmark costs and production data with the aim of identifying inefficiencies. However, due to the plentiful volume of virgin timber and cheap labor at the time even the most inefficient logging operations survived, and the concept of control never gained wide acceptance as it did in other industries.

Control in forest operations, including cost control deals with a much larger area than accounting and is concerned with improved operations, future planning and conservation of resources. Production data are essential, and normally the relations between inputs and outputs are shown in pure physical terms, in contrast to cost and price data which show economic relations only (Silversides and Sundberg 1987). These measured relations of inputs and outputs dictate ones influence or level of control over an operation and are known as measures of operational efficiency. Operational efficiency is to economize human or man-made inputs, or to allocate in time and space labor and machines in a rational fashion (Sundberg and Silversides 1987). Such problems in operational efficiency can be categorized into three main categories:

1. Social- Primarily concerned with social and living conditions of the labor force: providing safe working conditions, minimizing hazards to health, designing work to the capability of workers and so that workers get satisfaction from earnings and values other than money.

2. Technical- Selecting the technical means which perform the job: input of man-made resources, machines or tools, the forest roads, communications and other fixed installations facilitating operations.
3. Economic-In general, performing the work to a satisfactorily low cost: balancing inputs of man, machines and other assets needed to perform the job whilst meeting the objectives.

For many years mechanization has been the most preferred and successful way of achieving operational efficiency for both classical forms of forestry. Mechanization of operations significantly increased productivity and capacity, while decreasing the requirement for labor which became increasingly expensive to employ (Figure 1.2).

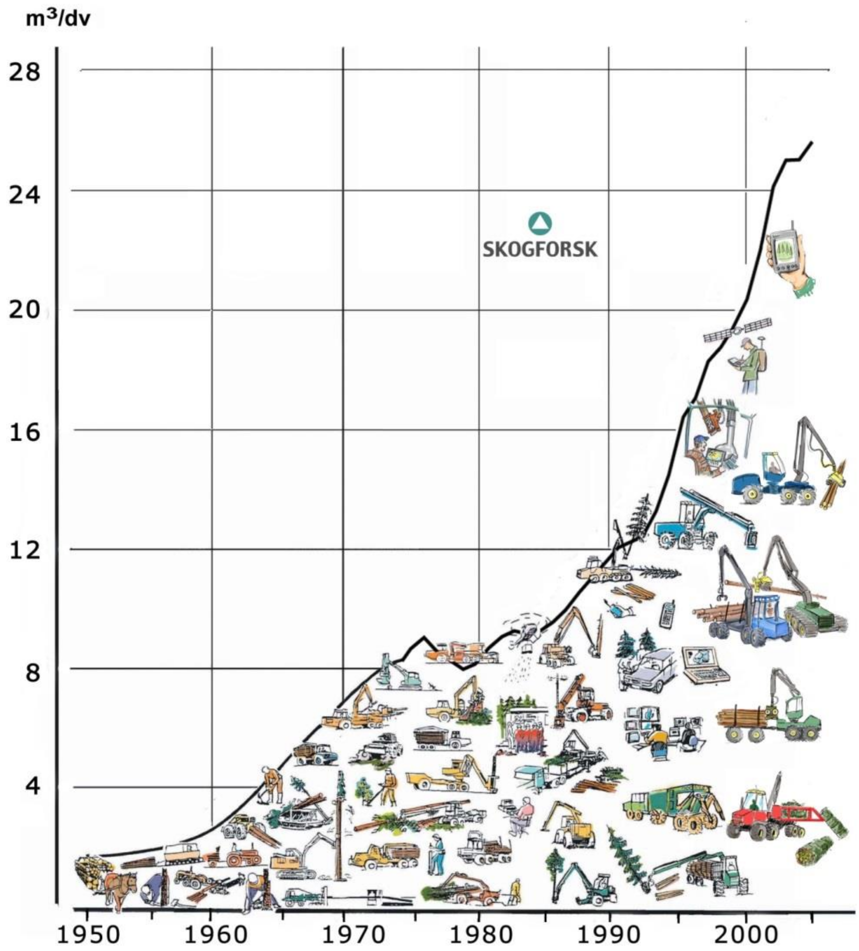

Figure 1.2: The trend in forest operations mechanization and the increase in productivity per unit of labor (m^3/day/worker), (SKOGFORSK 2014).

However, along the years of developments there were periods where profitability reduced to an extent where a new method or machine was developed; requiring a step change in the harvesting process. This is referred to by Samset (1985) as the "law of discontinuous evolution," (Figure 1.3). The law can be observed in several different stages: Stage one is "price pressure" where increasing costs erode profitability. Stage two is when new developments emerge and are trialed. Stage three is when the successful new developments are introduced, which exhibit a sharp learning curve. Stage four is when the new developments are stabilized and become widely used.

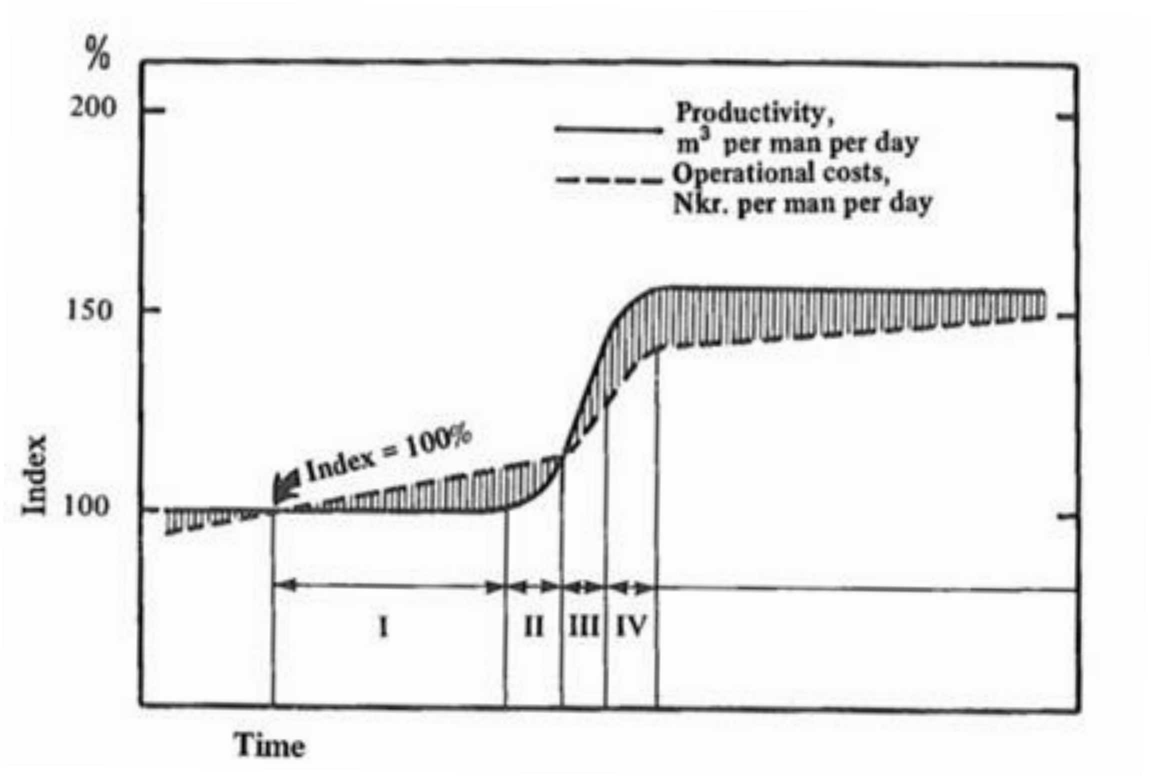

Figure 1.3: Stages of discontinuous evolution for harvesting systems (Samset 1985).

Nominal costs of any logging operation will always increase over time; however, the only way to decrease the operational costs is to introduce new methods (techniques), a new organization of the work (planning), or by introducing new equipment (Samset 1985).

1.1.6 Rigging Configurations

There are many different methods that can be used when cable logging. First, we commonly differentiate these by what skyline system is being used (i.e. none, standing, live, or running). Furthermore, we then classify which types of additional gear (i.e. ropes, carriages, and blocks) are used into a specific category called a rigging configuration. For example, Figure 1.4 is a schematic of a standing skyline system using a slackline carriage configuration. There are a number of different rigging configurations which can be used, and some are more preferred than others in a given location (Liley 1983; Studier and Binkley 1974). Deciding which rigging configuration to use can be challenging and is usually chosen based on the available equipment, the site conditions, among many other variables; but is often chosen based on the experience and preference of the crew.

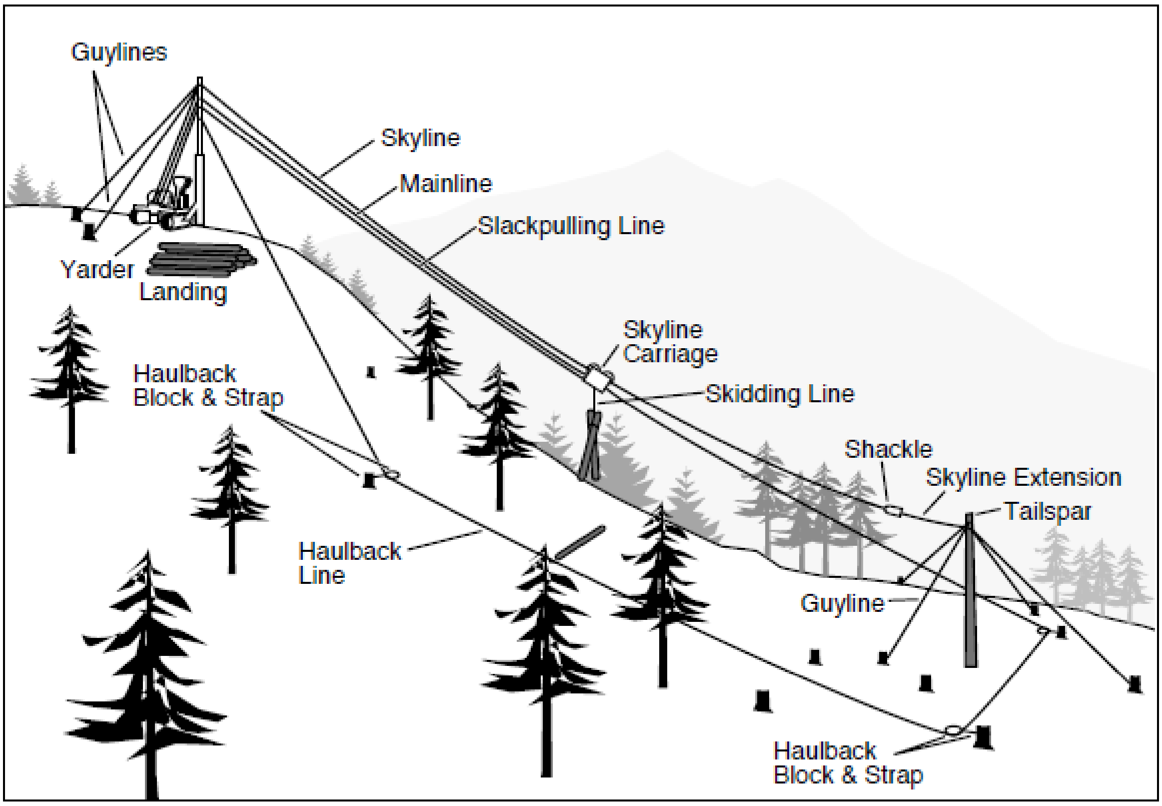

Figure 1.4: Basic concept of using cable to extract timber: Cable logging system utilizing a standing skyline and slackline carriage (Studier 1993).

Improvements can come about through new machines, equipment and methods. However, these must be studied through extensive field testing to determine their effectiveness and optimal application, and some may take years. However, there is always room for improvement in our daily operations. Therefore, it is not entirely necessary to “reinvent the wheel” or for that matter new methods and equipment. Better understanding of the capabilities and limitations of present methods (i.e. rigging configurations) and machinery and how to optimize these will lead to improved production and economic viability of these systems. Furthermore, a better understanding of these systems permits more precise and effective planning for future operations which is paramount for reduced infrastructure cost, minimizing environmental disturbance, improved operational efficiency and safety.

1.2 Statement of Objectives

The key objective of this thesis was to help improve industry understanding of rigging configurations used in New Zealand cable logging operations, with the following specific objectives:

1. Determine by way of field survey, what types of cable logging systems and rigging configurations are currently used in New Zealand, and what knowledge gaps exist.

2. Establish using survey results and an expert panel, characteristics of rigging configurations, including their true advantages and disadvantages.

3. Using a scale model yarder, measure the dynamic skyline tensions for various rigging configurations and establish where and how they differ.

4. Through field study quantify and compare the productivities of the most commonly used rigging configurations operating in typical New Zealand stand and terrain conditions.

5. Through field study measure skyline tensions and compare them between the most commonly used rigging configurations, operating in similar New Zealand stand and terrain conditions.

6. Provide recommendations for potential improvements to New Zealand cable logging operations.

1.3 Thesis Layout

This thesis research investigates the stated objectives to provide a better understanding about cable logging systems used in New Zealand. The research consists of a series of projects ranging from literature reviews, surveys and case studies which build upon one another. Greater understanding of cable logging systems in New Zealand should achieve higher productivity, reduced costs and potentially improved safety for future operations. Chapter 2 is a comprehensive literature review into previous cable logging research worldwide was performed. Chapter 3 is the survey to determine which cable logging methods were being used in New Zealand and what was known about them by practitioners. The survey also consisted of a second part where an expert panel, using a Delphi process, clarified misconceptions or understandings of survey participants to produce lists of the true advantages and disadvantages of each method (i.e. rigging configuration). Chapter 4 used a model yarder to evaluate three similar rigging systems and quantify and study their dynamic skyline tensions. Study of actual cable logging sites, with results of dynamic skyline tensions and productivity of rigging configurations, is presented in Chapter 5. Finally, Chapter 6 provides an overview of these various research projects and discusses the implications of their main findings.

Chapter 2: Literature Review

2.1 Cable Logging Practices

Logging is a specialized form of materials handling and transportation, where the materials being handled vary from logs to whole tree stems. Using cables to extract felled stems rather than horse or oxen emerged as a common practice around the turn of the 20th century, and became known as cable logging a preferred method of extraction on steep slopes (Studier and Binkley 1974). Cable logging practices date back centuries in Europe, but modern cable yarding practices were developed in the late 19th century with the advent of steam powered engines like the Dolbeer Steam donkey in 1881 in Eureka, California (City of Eureka 2010). The machinery used has improved over the years from the early steam powered winch sets to current yarders with highly-sophisticated diesel powered engines, air controls, water-cooled brakes and interlocking drums. However, the problem and solution remains the same; to get some “lead” or upward lift on the logs to provide partial or full suspension of the logs to avoid ground objects and reduce the friction and thus the pull required to transport the material.

Modern cable logging with integrated tower yarders (referred to as haulers in New Zealand) was introduced into plantation forestry in the 1950’s, with the development of diesel yarders, and has continued to be the preferred method of extracting timber on slopes limiting conventional ground-based equipment around the world (Kirk and Sullman 2001). There have been numerous developments in the methods of cable logging and practices differ world-wide. Cable yarding is also preferred due to its’ environmental benefits over ground-based yarding, because the partial or full suspension of logs generated results in minimal soil disturbance (McMahon 1995; Visser 1998). Alternatives, such as modified ground-based equipment and helicopters exist for the extraction of timber on steep slopes. Helicopters are not often preferred due to their high rate of fuel consumption and expensive operating costs. To date, modified ground-based equipment is limited in their application due to their short economic yarding distance and their difficulty in traversing rough terrain. However, new equipment options are being developed to push the limits of ground based machinery on steep terrain (Evanson and Amishev 2010). However, as ground based machinery become increasingly dangerous and less productive to operate on steep terrain (> 45% slope); cable extraction of stems still remains as one of the only viable options for harvesting.

Despite its wide use and environmental benefits cable logging is expensive and is more complex than either tractor or skidder logging. It has a high incidence of accidents to workers and is generally less productive than ground-based methods of harvesting timber (Slappendel et al. 1993) . Cable logging as it is practiced in New Zealand differs in several respects from how it is practiced elsewhere. The reasons are various, but the nature of Pinus *radiata,* the value of the wood recovered, features of New Zealand's terrain and climate, and the reliance on plantation forestry, are all factors (Liley 1983).

When using a yarder for cable extraction the main criteria determining the extraction method to be used is the ground slope or profile of the area to be harvested (Visser 1998). The first decision made is whether the extraction of timber will be uphill or downhill. Then there are a variety of factors including desired lift, tower height of the yarder, number of drums for the yarder, crew size, and availability of carriages and gear, to name a few, which all determine which rigging configurations can be used. There are about ten different basic cable yarder rigging configurations and literally hundreds of variations when including different carriages and attachments. Therefore, a given stand of timber has no one wrong or right method for extracting the timber.

2.2 Rigging Configurations

When defining a cable logging method practitioners first describe the operation by which system is being used. A cable logging system is defined by the type, number and the functions of cables or wire ropes (Kendrick 1992; Studier and Binkley 1974). There are four main types of cable logging systems: highlead, standing skyline, live skyline and running skyline. After defining the cable logging system practitioners then further define the cable logging method by what’s called a rigging configuration. A rigging configuration refers to the gear/rigging (i.e. blocks, geometric arrangement of ropes and carriage type) being used. Some rigging configurations can be used between systems while others cannot. For instance, motorized carriages can be used in standing, live or running skyline systems, while Grabinski (i.e. scab) is a rigging configuration exclusive to the running skyline system.

Each rigging configuration has its own set of capabilities and limitations and it’s the job of the forest engineer or harvest planner to appropriately match them to a given site in order to satisfy the land owner’s objectives. However, the natural environment in which we apply these operations is highly variable; making the process of planning very difficult especially when trying to estimate potential outcomes, whether they are financial, social or environmental. Because of these complexities with the natural environment the topic of cable logging has received a great deal of attention and has been the subject of many scientific research projects within the forest industry. While the latter sections of this literature review briefly describe and list a selection of these scientific reports, a number of cable logging manuals have also been developed over time. These manuals are often a great starting point for reading as they summarize best practices based on current state of knowledge.

2.3 Manuals

1. LIRA Cable Logging Handbook - Overview document published in 1983. Includes charts to help calculate payloads for various setting and rigging types.
2. Best Practice Guidelines for Cable Logging - NZ Forest Industry Training and Education Council published in 2005; combines industry training standards, Approved Code of Practice (ACOP) rules, hazard management, and Best Practice information to provide a reference manual for practitioners.
3. Yarding and Loading Handbook - Oregon OSHA – comprehensive overview of many of the elements and processes within cable logging, including many very good illustrations. (www.cbs.state.or.us/osha/pdf/pubs/1935.pdf)

4. Cable Yarding Systems Handbook - WorkSafe British Columbia published in 2006 - http://www.worksafebc.com/publications/health_and_safety/by_topic/assets/pdf/cable yarding.pdf
5. Grapple Yarding and Supersnorkel Handbook - WorkSafe British Columbia Revised 2011- Guide specifically aimed towards grapple yarding systems with many familiar charts and references from Cable Yarding Systems Handbook.
6. Harvesting Systems and Equipment British Columbia - MacDonald (1999); guide for selecting appropriate harvesting equipment and systems including charts for comparison and dichotomous key for decision making.
7. Guide for Managing Risks in Cable logging - Safe Work Australia**;** http://www.safeworkaustralia.gov.au/

2.4 Books

1. Cable Logging Systems – Studier and Binkley (1974); One of the original and most complete references to cable logging in North America.

2. Cable Logging Systems - FAO (1981); European version of complete cable logging reference.
3. Winch and Cable Systems – Samset (1985); civil engineering handbook on winch and cable systems, with content based on 35 years of experience with winch and cable operations as leader of the Norwegian Institute of Forest Operations.
4. Wire Rope Splicing Handbook – Simpson (1984); a LIRA guide to splicing wire ropes in forest operations.

2.5 Software

1. LoggerPC - (latest version was 4.2) Jarmer and Sessions (1992)-Very universal Windows based program, freely available and easy to use. An excellent tool for teaching and analyses of single corridors.
2. SkylineXL- Effectively LoggerPC transferred to excel spreadsheet to avoid any Windows type problems.
3. PLANS - developed by the USDA Forest Service (Twito et al. 1987) has been used for developing timber harvest and road network plans based on large-scale topographic maps. The model provides useful information, such as payload analysis, cost analysis, road layout, and terrain information.
4. RoadEng – developed by Softtree. It is primarily road and surveying software, but has a Forestry module that includes the opportunity to analyze cable corridors. Especially good if planning road layout with regard to cable logging feasibility.
5. PLANEX - (Epstein et al. 2001) is able to generate an approximately optimal allocation of equipment and road network based on a heuristic algorithm. System does not have the ability to analyze cableways with their topographic profiles.
6. CYANZ (Cable Yarding Analyses New Zealand) – Developed by Forest Solutions Ltd as an integrated application for optimizing cable logging extraction. (www.cyanz.com/).
7. CHPS (Cable Harvesting Planning Solution) – new software developed by GBS as an add-in module to ESRI GIS.

2.6 Overview of cable logging research

Research into cable logging operations has been conducted world-wide by numerous individuals and organizations over the years, some carried out by logging contractors, universities, private companies and public or government agencies. Because cable logging is not as common or popular as ground-based methods, there has been comparatively less research on the topic. However, since it's immergence as a practice there have been some great contributions to research. The main regions making early and regular contributions to the field of research have been the forested mountainous regions with existing or mature forest industries where the practices of cable logging originated, like the Pacific Northwest (PNW) of the Americas and central Europe. In more recent years, regions with maturing forest industries where interest in cable logging has increased like Japan, New Zealand (NZ), and parts of South America and Eastern Europe have increased their contribution to research.

The US Forest Service was particularly active in cable logging research between 1960 -1990, particularly through their collaboration with Oregon State University via their forest engineering graduate program. The US Forest Service faced the challenge of increasing their proportion of annual harvest on steep terrain, which were marginally economic at the beginning of the 1960's, such that they felt compelled to train more than 500 specialists in less than a decade (Carson 1983). Many of the developments during this time period aimed to reduce man power as it became more expensive, but skilled labor also became harder to obtain and worker accidents and fatalities were increasingly a concern (Christensen 1978). A few of the more relevant studies during this time period and more recent ones have been summarized in and will be discussed in further detail.

The objective of this literature review is to outline the general topics of cable logging research and highlight the most applicable studies to NZ plantation forests within those topics. The aim is to provide scientific resources to aid in education as well as research and development efforts towards steep terrain harvesting in New Zealand plantation forests. Figure 2.1 provides an overview of the types of studies that have been carried out, as well as highlighting relevant publications for each category.

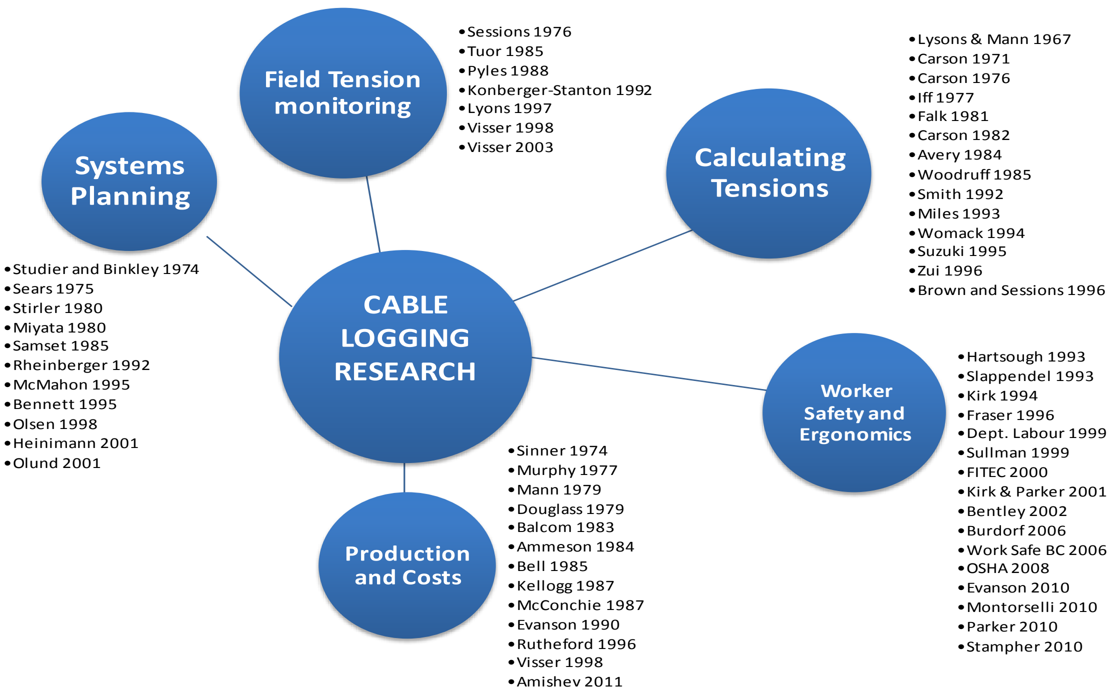

Figure 2.1: Topics in cable logging research and individual papers associated.

2.7 Systems and Planning

Studier and Binkley (1974) established one of the best guides earlier to cable logging, which built on the fundamentals of the skyline tension and deflection handbook from Lysons and Mann (1967). LIRA later developed its own version of the cable logging handbook for New Zealand (Liley 1983). The Norwegian Ivar Samset published a cable logging textbook that was subsequently translated into English "Winch and Cable Systems", which was very detailed with formulas and integrated 40 years of research work in cable logging in Europe and around the world (Samset 1985). Interest in European systems brought about a project in carriage development for endless line systems used with conventional yarders in thinning operations (Sears 1975). With more machines becoming available, a method of selecting cable harvesting machines in Vermont forests was developed using desktop computers (Stirler 1980). Formulas for calculating equipment ownership and operating costs (i.e. machine rate) became necessary for such an analysis (Miyata 1980). Different types and specification of ropes became more available, warranting a study on selecting wire rope design factors in cable logging (Rheinberger 1992). Soil disturbance resulting from New Zealand cable logging operations became an increasing concern internationally and was investigated (McMahon 1995). Alternative rigging options for the North Bend configuration were studied as it became a common practice and practitioners looked to solve some potential disadvantages (Bennett and McConchie 1995). Statistical methods used in time studies and how to apply them were explained in an attempt to provide a foundation for future production and cost studies (Olsen et al. 1998). Perspectives on European cable yarding systems and how they differ from the rest of the world (Heinimann et al. 2001), as well as the future of cable logging operations were discussed (Olund 2001).

2.8 Tension Monitoring

Most research in cable logging tensions in the past has focused on how to mathematically calculate and model static tensions for various systems and rigging configurations: like the Skyline Tension and Deflection Handbook (Lysons and Mann 1967); running skyline load path (Carson and Mann 1971) later revised and transferred on to programmable desktop calculators (Carson 1976); analysis of slackpulling forces in manual thinning carriages (Iff 1977); analysis of guylines (Carson et al. 1982); lateral yarding forces (Falk 1981); tethered balloon logging (Avery 1984); analysis of North Bend, South Bend and Block in the Bight configurations (Woodruff 1984); remote tension monitoring for yarders (Smith 1992); clamped and unclamped carriage tensions including downhill logging (Miles et al. 1993); analysis of triangular running skyline system (Suzuki et al. 1996); formulas for the vibration method of estimating cable tension (Zui et al. 1996). Field measurement of wire rope tensions were conducted for several systems and rigging configurations including: indirect measurement of cable tension and vibration using lasers (Kroneberger-Stanton and Hartsough 1992); a maximum log load solution procedure (Brown and Sessions 1996) skyline and guyline tensions measured at tail spars (Lyons 1997); clamped and unclamped carriages effect on skyline tension (Miles et al. 1993); static tensions of guylines at tail spars (Pyles 1988); field measurement of skyline deflection and tension using vibration method (Sessions 1976); static forces in pendulum balloon logging (Tuor 1985); tension monitoring of forestry cable systems (Visser 1998); forces in wire rope slings used to prevent log loss on steep slopes (Visser 2003).

Safe working loads in logging operations typically suggest to keep loads under one third of the rope's tensile strength (safety factor of three) in order to account for both static and dynamic loading (Liley 1983). Many accidents in cable logging happen when there is a failure in the equipment or wire ropes used, and various studies over the years have investigated these potential failures and the benefits that tension monitoring provides (Fraser 1996; Fraser and Bennett 1996; Hartsough 1993; Smith 1992; Visser 1998). Few researchers with the exception of Womack (1994), Pyles et al. (1994) and Visser (1998) have investigated the dynamic forces in wire ropes used in cable logging. There is a gap in knowledge as to when or why safe working loads are exceeded during logging operations. There is limited understanding of the dynamic forces generated during logging, and whether static or dynamic forces differ between various rigging configurations.

2.9 Safety and Ergonomics

Many guide books on cable logging safety and best practices have been produced over the years to educate workers to reduce accidents. Notably the Yarding and Loading Handbook by OR-OSHA (1993) and revised (2008), which built on the Cable Yarding Systems Handbook by WorkSafeBC (2006) and subsequent versions. Similar guides exist in New Zealand like the Approved Code of Practice by the (Department of Labour 1999) and the Best Practice Guidelines by (FITEC 2000). Unfortunately, worker fatalities occur in the same ways as they were 40 years ago (OR-OSHA 2008). Improving our knowledge of forces and tensions involved with complex cable logging systems, as well as a better understanding of control over the extraction process, can help improve safety. (Slappendel et al. 1993) investigated factors affecting work related injury in forest workers in New Zealand. Hartsough (1993) investigated the use of remote tension monitors and the benefits to safety they provide. Physical demands of steep terrain workers were quantified by Kirk and Parker (1994), and later investigated heart rate and strain of choker setters (Kirk and Sullman 2001). Yarder tower collapses became a concern prompting two studies by Fraser (1996) and Fraser and Bennett (1996) on hauler collapses and potential causes. The New Zealand accident reporting scheme was established to combat increasing rates of accidents (Sullman et al. 1999). Bentley et al. (2002) outlined how the accident reporting scheme data could be used to identify priority areas for ergonomics safety and health research attention. Danish researcher Burdorf et al. (2007) investigated effects of mechanized equipment on the physical work load of laborers in road building. Montorselli et al. (2010) quantified safety and productivity of motor manual operations in the Italian Alps; while back in New Zealand the use of video clips from cameras mounted on forest workers and their effectiveness in training was investigated (Parker 2010).

2.10 Productivity

System productivity has been extensively researched in logging operations, as increasing productivity typically results in lower logging rate costs ($/ton or $/m^3) (Visser 2009). An example of studies that provided insight and understanding into production potential of various logging systems and rigging configurations was known as the Pansy Basin Studies carried out in the Pacific Northwest. Production rates and costs for cable, balloon and helicopter yarding systems in old growth stands where established (Dykstra 1975) with a follow up study on the same systems in thinned and clearcut young growth forests (Dykstra 1976a). A further investigation into system's delays was also published by (Dykstra 1976b). There were other research projects carried out at the time such as : running skyline production using a mechanical slack pulling carriage (Mann 1979); Production of a manual slack pulling carriage in thinned stands (Sinner 1973); comparison of skyline carriages for small wood harvesting (Balcom 1983); production of pendulum balloon logging (Ammeson 1984); production costs and optimal line spacing of running skyline and standing skyline systems using slack pulling carriages (Rutherford 1996).

Amishev (2011) investigated what factors affect cable yarding crew performance in forest operations in New Zealand. Improved performance through efficient extraction by estimating and optimizing payloads was investigated (Visser et al. 1999). Others quantified systems production rates, and even compared production rates of different systems and equipment side by side over the same terrain and stand conditions such as; comparison of Washington 88 and Madill 009 (Bell 1985); cycle time comparison of Timbermaster and Wilhaul yarders (Douglass 1979); shift level comparisons between Ecologger, Bellis, Lotus, and Thunderbird yarders in down-hill logging (Evanson 1990a, b); and a case study of a mobile Madill 90S in mature radiata pine (Murphy 1977). These studies and many other yarder trials carried out by LIRA/LIRO between 1973-1991 have been summarized in a book by Harper (1992). Some have investigated different rigging systems and their productivities such as: alternative rigging variations for the North Bend configuration to improve productivity by improving control and reducing required line shifts (Bennett and McConchie 1995); and a system evaluation of a Madill 071 using North Bend, Shotgun, Slackline and mechanical slack pulling carriage configurations, published as four separate reports (McConchie 1987a, b, c, d).

Very few studies have compared the production rates between various rigging configurations using the same equipment in similar conditions. An exception is Kellogg (1987), who compared three different rigging configurations on similar stands of timber. Few studies have investigated fuel consumption in cable logging operations, or have compared fuel use between rigging configurations. Cable yarding machines consume between 20-40 L/hr, and up to three times as much fuel per ton of wood harvested than ground based systems (Gordon and Foran 1980).

2.11 Rigging Configurations

There has been considerable interest around rigging configurations and their appropriate uses in the last few years[1]. A recent survey of cable logging practitioners by Harrill and Visser (2011) found that cable logging practices differ in New Zealand from other countries with a strong dependence on three non-carriage configurations, namely North Bend standing skyline and Grabinski running skyline. Results also indicated that participants had a good understanding of the other configurations as well as strong interest in their versatility and perceived advantages. However, only 28% had tried any of the other configurations in the last five years. The survey work was expanded the following year to include an expert panel who discussed the true advantages and disadvantages of each rigging configuration mentioned by survey participants (Harrill and Visser 2012). With a strong dependence in NZ towards the North Bend configuration, research then attempted to quantify the differences in dynamic tensions between North Bend and the other similar fall block configurations using a model yarder (Harrill and Visser 2013). Research work should continue investigating rigging configurations, *"the most successful loggers have a variety of carriages and configurations at their disposal and they have an excellent understanding of the optimal application of each one…whenever the opportunity arises to improve costs by changing configurations, they do so." (Hemphill 1985).*

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[1] Tuor, B.L. Cable Logging Specialist. 3650 Ridge Rd, Mabton, WA, USA. 23, February, 2011. E-mail.

2.12 Research Trends

An insight into international cable logging research from the period from 2000-2011 was summarized in a literature review by the Italian Cavalli (2012). The majority of works comprised in his review were from conference proceedings followed by scientific journal articles and the vast majority, were from countries other than the USA and New Zealand. Cavalli found that the last 10 years of research by forest engineers interested in cable logging was directed mainly (45%) towards efficiency (Figure 2.2).

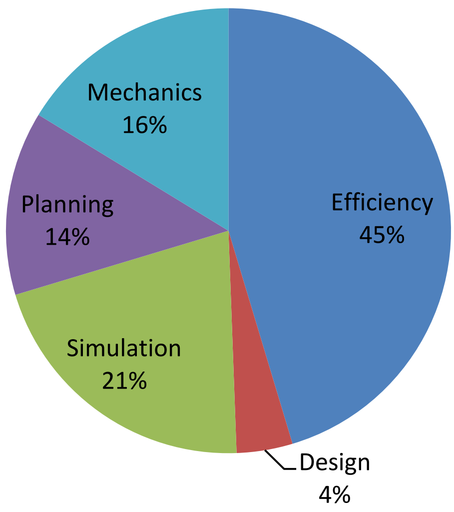

Figure 2.2: Topics of cable logging research 2000-2011 (Cavalli 2012).

With increases in the cost of labor and fuel, and increasing global market competition, there will be increased focus on operational efficiency (Visser et al. 2011). Reduction in energy expenditure (kW) and fuel consumption, as well as automated controls for improved safety, worker satisfaction and a reduction in man power, has increased the interest in modern, mainly European designed, yarders. Cavalli (2012) goes on to state that in the near future efficiency will continue to be the topic in cable logging research and that efforts in optimization including computer automation and control of machinery will aid this focus on efficiency. Of interest will be how a country such as New Zealand transitions into this new cable logging era through research and development efforts.

Chapter 3: Survey of Rigging Configurations and Equipment Used in New Zealand Cable Logging Operations

Contents of this chapter have been published as:

Harrill, H., and R. Visser. 2011. Rigging configurations used in New Zealand cable logging. Future Forests Research Ltd. (FFR). HTN03-11. 6.

Harrill, H., and R. Visser. 2012. Matching rigging configurations to harvesting conditions. Future Forests Research Ltd. (FFR). HTN04-06. 8.

3.1 Introduction

Cable yarding practices vary widely worldwide from the Pacific North West of the USA to Europe. In the Pacific North West there is a preference for large tower yarders and the use of motorized carriages when and where possible. In comparison, central Europeans prefer more automated small or medium-sized yarders with mechanical slack-pulling carriages.

Cable logging practiced in New Zealand differs in several respects to the USA and Europe, especially with the preference in New Zealand towards 'live' skyline rigging configurations such as North Bend, running skyline and shotgun (Harrill and Visser 2011). The reasons are various, but the nature of *Pinus radiata*, the value of the wood recovered, the features of New Zealand's terrain and climate, and the reliance on plantation forestry, have been explained as factors (Liley 1983).

In the first part of this project a survey of logging practitioners was undertaken aimed at determining which cable rigging configurations are commonly known and used in New Zealand. The survey gathered practitioner's opinions about the advantages and disadvantages of the common rigging configurations in use. It also investigated preferences for specific scenarios.

The second part of the study analyzed the perceived advantages and disadvantages using an expert panel that synthesized common elements of the individual responses gathered in the survey. This report presents the survey information relating the preferred rigging configurations to stand and terrain conditions. The purpose is to provide guidance to logging practitioners and planners in deciding which configurations are most suited to specific locations.

3.2 Methods

3.2.1 Interview Process

A questionnaire was developed and interviews were conducted in person from a variety of regions in New Zealand. The full questionnaire is in the appendix. The rigging configurations referred to in this report are as presented in Studier and Binkley (1974). During visits to active logging operations, forest management offices, and equipment manufacturers, interviews were conducted with the most knowledgeable and experienced person with cable yarding on site. Individuals who contributed to the study had the option to remain anonymous. Basic information collected included; job title, the company they worked for, equipment they owned, and which rigging configurations they were most familiar with. Then the advantages and disadvantages of each rigging configuration were noted. Finally some terrain scenarios were discussed in terms of which rigging configuration might be best suited. Each of the interviews asked the same questions in the same order so that the answers could be easily compared from person to person and region to region.

Interview data was then entered into Microsoft Excel 2010[2] spreadsheet software. Summary statistics as well as graphs and tables were then generated for each of the interview questions using functions within excel.

3.2.2 Delphi Process

Once all interviews were complete and the results were summarized, an expert panel of 5 individuals with the greatest knowledge and experience were selected by the research team.

[2] Microsoft Excel Version 14.0.7109.500. Microsoft Corp., Redmond, Washington, USA

The goal of the expert panel was to synthesize the responses from the interviews and provide their expert opinion to conflicting responses and viewpoints over the course of several rounds, in what is called the Delphi process (Dalkey and Helmer 1962). Panel members were emailed the interactive ranking spreadsheet software where they recorded their ranks and comments, and then emailed them back to the research team after each round. Each of the expert panel members remained anonymous to one another, but were able to view how others ranked the responses once each round was complete.

The panel members comprised:

- Daniel Fraser, Hikurangi Forest Farms Ltd, Gisborne
- Alan Paulson, HarvestPro NZ Ltd, Gisborne
- Brian Tuor, Independent Consultant, Washington, USA
- Brett Vincent, FITEC, Rotorua
- Rob Wooster, Moutere Logging Ltd, Nelson

In round one the panel was given the tables produced from interview questions regarding rigging configuration's advantages and disadvantages (Table 3.1 to Table 3.8). The expert panel members then ranked each response of a rigging configuration's advantages or disadvantages on a four point scale (1: strongly disagree to 4: strongly agree). In round two panel members were given the opportunity to change their rankings and provide comments about why they kept their ranks the same or changed them. The Delphi process was complete once the expert panel members reached a consensus on rankings after round three. In some cases a consensus can't be reached, and a more appropriate way of determining closure is when rankings of responses remain stable between rounds (Hasson et al. 2000). Reliance should not be placed on the Delphi process, as it has been found to be most useful in gathering opinions from large numbers of peoples and as a heuristic device rather than a means of predicting the future (Fisher 1978; Hasson et al. 2000; Linstone and Turoff 2002).

3.3 Results and Discussion

3.3.1 Survey Participation

A total of 50 interviews were conducted, from eight different regions in New Zealand and one region in the United States (Figure 3.1). Most (52%) were from the North Island, although Otago/Southland on the South Island was equally one of the most heavily sampled regions (20%). The majority of interviews were with crew owners who acted as foreman, followed by company planners, crew foreman, and yarder operators. Interviews were also given to equipment operators and in some cases crew owners not onsite with their logging crews.

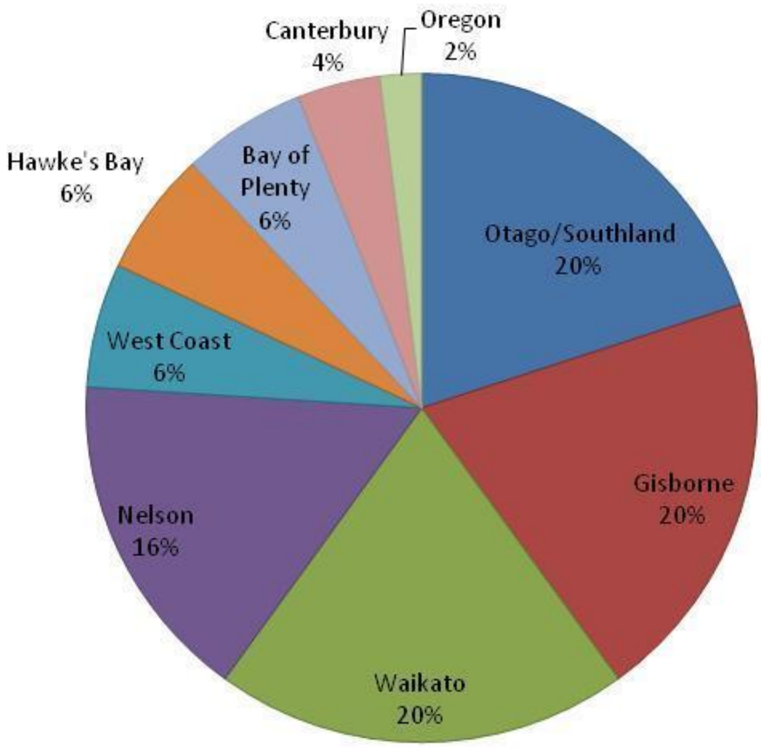

Figure 3.1: Regional spread of survey participants.

3.3.2 Use and Knowledge of Rigging Configurations

When asked which rigging configuration they most often used 48% stated North Bend, while the second most common configuration was Running Skyline followed closely by shotgun carriage (Figure 3.2). Despite North Bend's popularity most had used various rigging configurations recently.

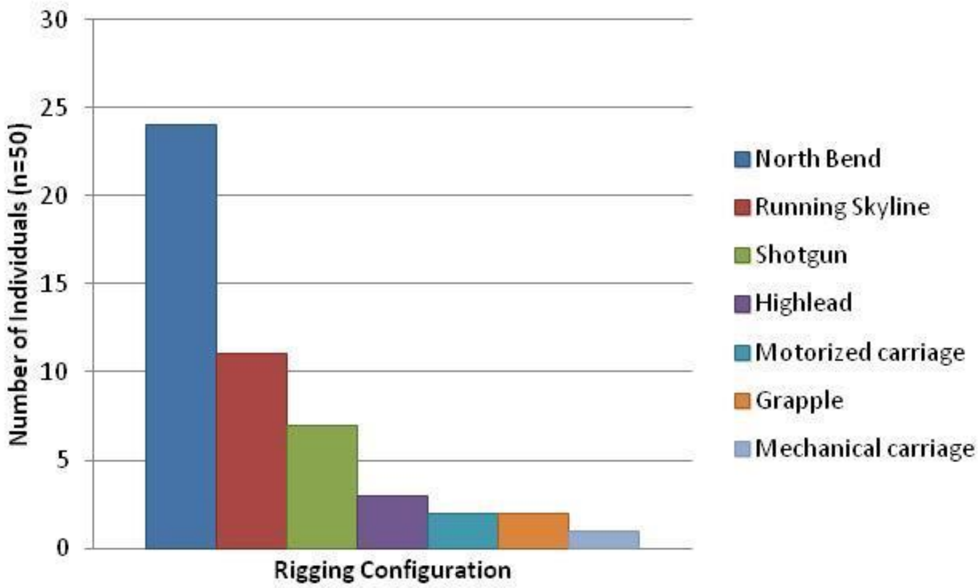

Figure 3.2: Rigging configuration most often used by survey participants.

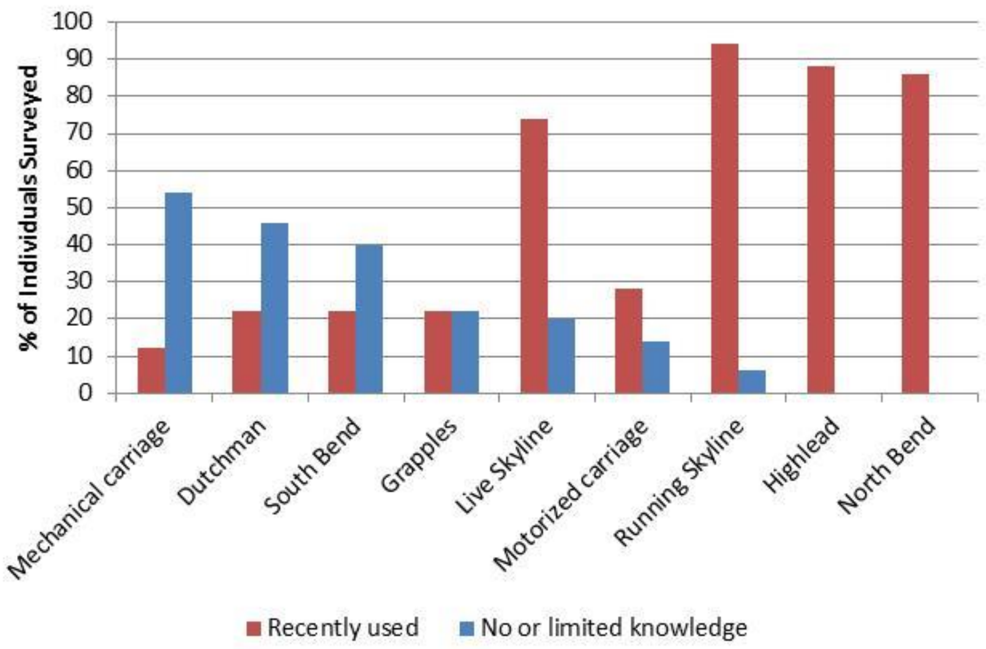

Figure 3.3: Study participant's recent use (last 5 years) versus no or limited knowledge of various rigging configurations.

More than 70% of survey participants said they had used Highlead, Running Skyline, North Bend, and Shotgun carriages within the last five years. However, it's interesting that 28% or less said they had used any of the other rigging configurations, including either motorized or mechanical carriages, within the last 5 years (Figure 3.3). Survey participants may be less likely to use alternate rigging configurations depending on terrain suitability or availability of personnel and equipment. However, the results indicate that perhaps they are deterred from using alternative rigging configurations because of their lack of knowledge or experience (Figure 3.3). The rigging configuration that most study participants (54%) said they had limited knowledge or experience with was mechanical carriages, which corroborates with only 12% saying they have used one in the last 5 years. Other configurations and equipment that individuals stated they had limited knowledge of were Dutchman, South Bend, and Grapples, all of which had limited use by study participants over the last 5 years.

A separate section of the interview asked participants about their experience and knowledge with swing yarders. The most recent survey in 2012 indicates that about 33% of all yarders currently operating in New Zealand are swing yarders (Visser, 2013), a substantial increase from 25% from a similar dataset from 2002 (Finnegan and Faircloth 2002). Only 46% of the participants were familiar enough to discuss them in detail and only some of them owned or used one. While, 16% stated they didn't know much about them at all or had never seen one working. This may explain why less than 25% of individuals have used a grapple in the last five years (Figure 3.3). Although many of the rigging configurations previously mentioned can be setup up with an integrated tower yarder or a swing yarder, some configurations like grapples are almost exclusively used in New Zealand on swing yarders. Many indicated that swing yarders were advantageous for short haul distances and their ability to work on small landings rotating and landing wood to the side out of the chute. Concerns with swing yarders were with their relatively short tower height and complexity, as well as their high cost.

3.3.3 Advantages and Disadvantages of Common Rigging Configurations

Brian Tuor, a consultant and trainer currently lives in Oregon but has worked extensively in New Zealand, concluded his response with the following statement[3]:

"In my experience, systems are often chosen not based on any or all of the criteria but on what the crew knows and are familiar with. This is not always bad, because given the wide overlaps in applicability of the systems, a crew is often more productive and safer using the system they know and are familiar with, rather than trying to learn and adapt to a new

[3] Tuor, B.L. Cable Logging Specialist. 3650 Ridge Rd, Mabton, WA, USA. 23, February, 2011. E-mail.

system. However this tendency keeps the crews from learning new and often more appropriate systems."

Some of the most informative and interesting results came from the discussions about the advantages and disadvantages associated with different rigging configurations and equipment. The following tables summarize these findings for the four most often used rigging configurations; Highlead, Running Skyline, North Bend, and Shotgun carriage. Responses were grouped during the analyses phase, and only those where three or more of the interviewees noted a similar advantages or disadvantage is presented.

3.3.3.1 Highlead

The most common advantages of Highleading were the simplicity in operation and setup, as well as its ability to function when there is limited to no deflection which prohibits most other configurations from being used (Table 3.1). Despite the advantages, Highleading's lack of lift poses a problem for the level of ground disturbance, breaking of gear and stems, and low productivity (Table 3.2).

Table 3.1: Advantages associated with Highlead.

Response	#
Quick to setup/Simple to operate	25
Good when there is limited deflection	19
Easy line shifts/No skyline	11
Good for short hauling distances	9
Ability to pull from blind areas	9
Productive system	8
Good last resort when nothing else works	7
Cheap system to run/Less expensive yarder	4

Table 3.2: Disadvantages associated with Highlead.

Response	#
No lift/Rigging drags on ground	31
Ground disturbance	17
Little control of drag/Drags get stuck/Breakage	19
Slow pulls = low productivity/Low Payloads	17
Rope wear	9
Chains tangle	7
Hard on breakerouts/Hazardous to workers	4
Fuel use is high	4
Loss of hp power due to braking tail rope	4
Limited to short distance/terrain conditions	4

3.3.3.2 Running Skyline (Scab or Grabinski)

The second most commonly used of all configurations was Running Skyline, which many prefer because like Highleading it is simple to setup and run, but it provides more lift (Table 3.3). The ability to make quick line shifts especially when using a mobile tail hold, and the increased lift is thought to increase overall productivity making Running Skyline one of the popular rigging configurations. Although Running Skyline is relatively quick concerns came with the configuration's payload capacity and yarding distance, as well as functional problems with gear such as line wrapping, rope wear, and brake wear. Its improved lift over Highlead is good but, often isn't enough to minimize soil disturbance or to be suited for all terrain conditions (Table 3.4).

Table 3.3: Advantages associated with Running Skyline (Scab or Grabinski).

Response	#
Simple/Quick setup & line shifts	30
Productive/Quick	19
Simple to operate/less skill required	17
Less ground disturbance/More lift than highlead	11
Minimal deflection required/Good for short distances	7
Easy to get slack in rope/Easy to land gear	4
Gear elevated off ground/Less rope wear	3
Can downhill yard	2
Less hp required/More pulling strength	3
More control over drag	3

Table 3.4: Disadvantages associated with Running Skyline (Scab or Grabinski).

Response	**#**
Rope wear & tangle/Gear break	17
Brake wear/Pulling against self/Tail pull	10
Short distances/Terrain limited	11
Lack of lift/need good deflection/need tall tower	14
Productivity/Smaller Payloads/More hp required	10
Fuel consumption	6
Soil disturbance	5
Lots of line shifts/Line shift time without mobile tail	3

3.3.3.3 North Bend

The most commonly used rigging configurations was North Bend, primarily because of its' versatility and ability to lateral yard due to bridling. Other common advantages were its robustness because crews find it hard to break and it's easy on the yarder and ropes, while still having good productivity and payload capability (Table 3.5). Despite being the most popular rigging configuration there were many disadvantages stated about the configuration. Most of the disadvantages had to do with longer setup time as well as longer and more complicated line shifts. The temptation to bridle to far often resulted in lower production and higher operating costs were of concern (Table 3.6).

Table 3.5: Advantages associated with North Bend

Response	#
Bridling capability/Lateral yarding/Versatility	25
Increased lift/Less soil disturbance	23
Productivity/Good payloads	18
Easy setup and rope shifts/Simple to operate	11
Robust/Hard to break/Easy on machine & ropes	8
Good control over drag/Getting around obstacles	8
Good for long distances	3

Table 3.6: Disadvantages associated with North Bend

Response	#
Longer skyline shifts/Tempted to bridle too far	12
Longer setup/Cost of operation	11
Production	8
Hard to drop gear to right location for hook-up	7
Suspension/Less control over drag/Breakage	6
Walk in & out for breaker outs	5
Lack of skill	5
Rope wear	5
Overloading hazard/Pull out stumps	4
Blind leads/Deep gulley’s	4
Long distance yarding	3
Landing and unhooking	3
Rider block and fall block hit together	3

3.3.3.4 Shotgun

Another one of the most commonly used configurations was live skyline with a Shotgun carriage. This configuration is very popular among users because highly regarded as the cheapest configuration to run due to its' limited fuel use. It is also very simple to operate and setup, productive, and tends to maximized deflection and payloads. It has good suspension of logs which often makes it a useful choice to fly logs over creeks or around obstacles (Table 3.7). Some of the disadvantages with this cheap configuration to operate are the expensive maintenance due to brake, rope, and gear wear. The configuration is also limited to terrain where you have a steep enough chord slope for gravity to outhaul the carriage. Although the concept is simple there is a hazard of overloading the skyline and therefore you need to have good communication and breaker outs need to be well trained (Table 3.8).

Table 3.7: Advantages associated with Shotgun.

Response	**#**
Maximizes deflection & payloads/Full suspension	19
Fuel use/Cheap to run	17
Productivity/Quick	16
Easy setup/Simple to operate	14
Less hp required	3
Easy on breaker outs/Easy to land logs & drop gear	3

Table 3.8: Disadvantages associated with Shotgun.

Response	#
Limited to terrain/Can't do back face without slack line	13
Brake, rope, & gear wear	7
Complicated/Harder line shifts	6
Overloading hazard/Need good communication	6
Deflection/Soil disturbance	6
Productivity	4
Hard to get caught drags unstuck	4

3.3.4 Variables for Selecting an Appropriate Rigging Configuration

3.3.4.1 Yarding Distance

Through the interview process it was evident that one commonly used factor for determining the appropriate rigging configuration was haul distance. Some rigging configurations like highlead are better suited for short distances while others are better suited for long haul distances. However, defining what is a short and what is a long haul distance proved to be a challenge. Most participants in the study would agree that somewhere around 300 meters or less is a short haul distance (Figure 3.4). When it came to determining what a long haul distance, responses varied even more. Most stated that more than 300 meters was long, but many would state that a long haul distance is greater than 400 meters and some would even say 500 (Figure 3.4). The results suggest that maybe we don’t understand these configurations at the 100 meter level of resolution or maybe there are more factors that come into play.

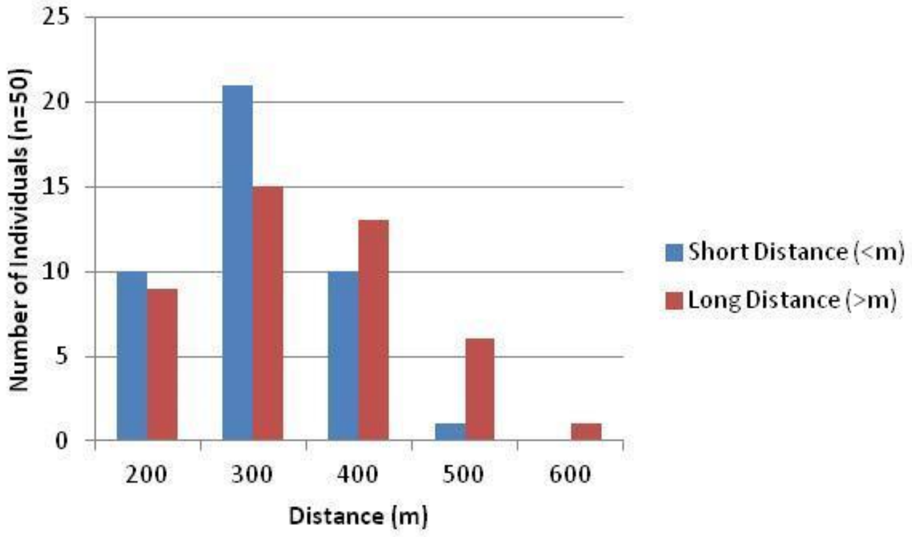

Figure 3.4: Participants’ definitions of long and short yarding distance.

When asked which rigging configurations were preferred for short and long hauling distances the answers again varied. Most individuals (32) would agree that Running Skyline would be a good option for short distances. Other than Running Skyline there were a variety of configurations that participants stated would work well for short haul distances including, shotgun, highlead, grappling, and even North Bend (Table 3.9). Statements on the preferred configuration for long haul distances were heavily concentrated to 3 different configurations. Half or more of individuals interviewed would agree that North Bend or shotgun are probably best suited for long distances followed closely by motorized carriages (Table 3.9). The choice of motorized carriage is interesting to note since only a few individuals stated they used them most often, and less than 30% say they have used one within the last 5 years.

Table 3.9: Participants' preference in rigging configurations for short and long haul distances.

Rigging System	**Short (#)**	**Long (#)**
Running Skyline	32	9
Shotgun	19	25
Highlead	15	1
Grapple	13	2
North Bend	12	29
Motorized carriage	7	15
Slackline	2	7
Mechanical carriage	1	2

3.3.4.2 Yarding Direction

Yarding direction is another main criterion for determining which rigging configuration to choose, since some configurations are not mechanically capable or are inherently dangerous to operate when pulling downhill. When participants were asked which configurations they preferred for pulling uphill the results were similar to which systems they use most often (North Bend, Shotgun, Running Skyline) this is most likely because most of the time they are yarding uphill. However, again note the preference to use a motorized carriage which are not commonly used yet 15 individuals said would work well (Table 3.10). For downhill yarding the preferences were concentrated to mainly two different configurations, Running Skyline and North Bend (Table 3.10). Most individuals said Running Skyline would work well and was preferred due to its simplicity, but many would also prefer North Bend for a little more control of the drag. Highlead and grappling were also common answers, highleading is not ideal due to associated ground disturbance, and grapples usually require the use of a swing yarder which many individuals do not possess.

Table 3.10: Participants preference in rigging configurations for uphill and downhill yarding.

Rigging System	Uphill (#)	Downhill (#)
Shotgun	34	0
North Bend	19	20
Motorized carriage	15	2
Running skyline	7	32
Grapple	4	9
Highlead	3	10
Mechanical carriage	2	0
South Bend	2	1
Slackline	2	6

3.3.4.3 Deflection

Deflection is probably one of the leading criteria for appropriate rigging configuration selection, since it ultimately dictates ground clearance and payload capacity. Often deflection is expressed as a percentage of the span length with low deflection being less than 6%, and high deflection being greater than 15%. When asked which rigging configuration was preferred given deflection alone the top four responses consisted of only six different rigging configurations (Figure 3.5).

Highleading was most popular for low deflection scenarios since it often works well with little deflection where others do not, and coincidentally it is not even considered when deflection is high or extreme. Running Skyline was the second highest choice for both low and medium deflection scenarios but then becomes less popular as deflection increases. North Bend was a popular choice and results show how versatile the configuration is since it was preferred in almost any deflection scenario. Although North Bend may be difficult to operate in low deflection settings, it is still most preferred configuration in medium, high, and sometimes extreme deflection settings. The shotgun configuration is another that works given most types of deflection. Shotgun never seems to be the first choice but higher consideration is given to the configuration as deflection increases. Grapples are considered to be preferable in any scenarios other than low deflection, but are less popular than other most likely due to other variables, but also because many crews do not own swing yarders which they are commonly used with and the limited experience and knowledge surrounding them. Most interesting to note was the preference for motorized carriages, which were selected for all deflection scenarios except for low, but again are not as widely used as other configurations. Motorized carriages appear to have a growing preference as deflection increases, and are the most preferred in extreme or very high deflection scenarios.

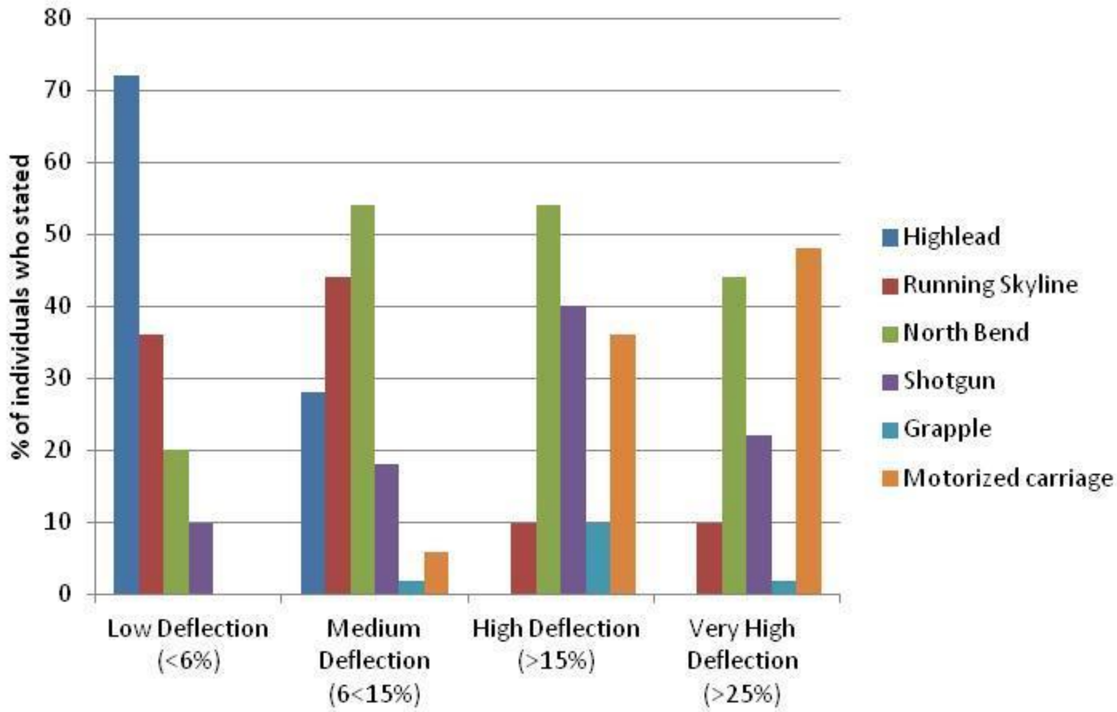

Figure 3.5: Participants' preferred rigging configurations given deflection conditions.

3.3.5 Operational Constraints Scenarios

Part of the interview process asked individuals which rigging configurations had the ability to handle certain operational constraints or challenges. Excluding all other variables participants then stated which configurations they thought would work best given the scenario.

3.3.5.1 Pulling Across Broken Terrain or Incised Gullies

Inconsistent terrain is a common challenge faced in New Zealand cable logging operations. Sometimes crews have to pull across several incised gullies or small ridges. This often times requires the load to be raised and lowered during inhaul to navigate potential obstacles. Most participants stated that North Bend was their preferred rigging configuration for this scenario, but motorized carriages were also given strong consideration (Table 3.11).

3.3.5.2 Having to Pull Away From or Around a Native Bush Boundary or Other Obstacle

Native tree species are not allowed to be harvested in New Zealand so any native patches of trees have to be protected and all operations are required to work around them. Pulling away from or around obstacles like native bush boundaries or rock faces often requires the configuration to have a lateral yarding capability. Again North Bend was the preferred choice for most participants due to its bridling capability. Motorized carriages were also highly regarded due to the slack pulling capabilities which allows them to lateral yard (Table 3.11).

3.3.5.3 Ability to Fly Trees Over a Watercourse or Stream Management Zone (SMZ)

Best management practice guidelines in New Zealand prohibit trees from being yarded through or drug across any major watercourse. The only acceptable way to yard across a watercourse is obtained through full suspension of the load, so there is no ground disturbance. Success if often determined by the ability to hold the load fully suspended during inhaul. Motorized carriages were the most common choice most likely due to their ability to lock the load in place at a given height while yarding across a watercourse (Table 3.11). North Bend and South Bend were also popular choices due to their vertical lifting abilities. However, the bend systems pose a slight challenge where the load can be unexpectedly lowered during inhaul if there is insufficient tension in the tail rope (haul back).

Table 3.11: Participants preferred rigging configuration for yarding across broken terrain, around native bush boundaries, and over Stream Management Zones.

Rigging Configuration	Across Broken Terrain (#)	Around Native Bush (#)	Over SMZ (#)
North Bend	27	33	15
Motorized carriage	16	21	33
South Bend	6	8	14
Slackline	5	3	9
Highlead	4	2	0
Shotgun	3	2	2
Running Skyline	2	1	3
Grapple	1	0	1
Mechanical carriage	1	1	0
Block in the Bight	0	3	0

3.3.6 Delphi Analysis

The following tables present the advantages and disadvantages associated with rigging configurations collected from interviews. These responses were ranked (1: strongly disagree, 2: disagree, 3: agree, 4: strongly agree) by the expert panel over three rounds of the Delphi process. An average rank of ≤ 2.0 indicates that the expert panel did not agree with the response, while and average rank of ≥ 3.0 means the expert panel did agree with the response. Average rankings between 2.0 and 3.0 indicate that there is not enough consensus between expert panel members about a response. The change in ranks by panel members between rounds is also presented, and a change of 0.0 between rounds indicates stability in panel members' opinions.

3.3.6.1 Highlead

Advantages of Highleading include the simplicity in operation, setup, line shifts, and the ability to function when there is limited to no deflection which prohibits most other configurations from being used (Table 3.12). Highleading is also one of the cheapest configurations to run requiring a simple and low cost 2 drum yarder. Despite the advantages, Highleading's lack of lift poses an assortment of problems; low suspension generally results in the stem and rigging dragging along the ground (i.e. ground lead). This log attitude provides little control of the drag and can cause higher levels of ground disturbance, a greater frequency of breakage and hang-ups, which can cause rigging to tangle and break easily so generally requires larger chokers; altogether these factors have compounding effects on productivity through slower cycles and more frequent delays which limit application to short distances. Fuel use is high compared to other configurations because of the need to break the haulback (tail rope) to generate lift which also results in a loss of horse power. Although manual shifting of line is not technically difficult, the larger heavier chokers required can be hard on the rigging crew and the unpredictable behavior of drags when in ground lead and the higher frequency of hang-ups can be hazardous to workers (Table 3.13).

Table 3.12: Advantages associated with Highleading.

	Round 1	Round2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Quick to setup/Simple to operate	3.6	3.6	0.0	3.6	0.0
Easy line shifts/No skyline	3.6	3.6	0.0	3.6	0.0
Cheap system to run/Less expensive yarder	3.4	3.4	0.0	3.4	0.0
Good when there is limited deflection	3.2	3.2	0.0	3.2	0.0
Good for short hauling distances	2.8	2.8	0.0	2.8	0.0
Good last resort when nothing else works	2.8	2.8	0.0	2.8	0.0
Less force on anchors	2.8	2.8	0.0	2.8	0.0
Ability to pull from blind areas	2.6	2.6	0.0	2.6	0.0
Good for downhill yarding	2.2	2.2	0.0	2.3	0.0
Productive system	2.2	2.2	0.0	2.2	0.0
Good for two staging	2.0	2.0	0.0	2.0	0.0

Table 3.13: Disadvantages associated with Highleading.

	Round 1	Round 2		Round 3	
Response	Avg. Rank	Avg. Rank	Change	Avg. Rank	Change
No lift/Rigging drags on ground	3.8	3.8	0.0	3.8	0.0
Ground disturbance	3.8	3.8	0.0	3.8	0.0
Little control of drag/Drags get stuck/Breakage	3.8	3.8	0.0	3.8	0.0
Chains tangle	3.6	3.6	0.0	3.6	0.0
Rope wear	3.4	3.4	0.0	3.4	0.0
Fuel use is high	3.4	3.4	0.0	3.4	0.0
Limited to short distance/terrain conditions	3.2	3.2	0.0	3.2	0.0
Slow pulls = low productivity/Low Payloads	3.0	3.0	0.0	3.0	0.0
Hard on breakerouts/Hazardous to workers	3.0	3.0	0.0	3.0	0.0
Loss of hp power due to braking tail rope	3.0	3.0	0.0	3.0	0.0
Need large chokers	3.0	3.0	0.0	3.0	0.0
Manual shifting of lines is hard	1.8	1.8	0.0	1.8	0.0

3.3.6.2 Running Skyline (Scab or Grabinski)

The second most commonly used of all configurations was Running Skyline, which many prefer because it's simple to setup, operate and shift lines, making it quick and productive (Table 3.14). Compared to Highleading there is improved log suspension which provides better control of the drag, the rigging is elevated off the ground and there is less ground disturbance. The configuration is also good for settings with short distances, little available deflection and can be used for downhill yarding. However, Scab still has many of the same associated disadvantages of Highlead which shares similar functions of wire ropes; where braking of the haulback is required to lift the payload which can result in greater brake wear, required horsepower and fuel use (Table 3.15). Although, some of these issues could be less of a concern if a more expensive interlocked yarder were to be used. Regardless, the configuration is limited in its lateral yarding ability, requiring more frequent rope shifts and is susceptible to rope wear and tangling with wire ropes operating close together; which is why many employ mobile tailhold for fast line shifts with spreader bars to prevent tangling. The configuration is usually limited to short distances with concave slopes and although it can be operated in minimal deflection settings it works better with increasing deflection and taller towers which help provide more lift.

Table 3.14: Advantages associated with Running Skyline (Scab or Grabinski).

	Round 1	**Round 2**		**Round 3**	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Simple/Quick setup & line shifts	3.8	3.8	0.0	3.8	0.0
Simple to operate/less skill required	3.6	3.6	0.0	3.8	0.2
Productive/Quick	3.6	3.6	0.0	3.6	0.0
Less ground disturbance/More lift than highlead	3.6	3.6	0.0	3.6	0.0
Easy to get slack in rope/Easy to land gear	3.4	3.4	0.0	3.4	0.0
Gear elevated off ground/Less rope wear	3.4	3.4	0.0	3.4	0.0
Can downhill yard	3.4	3.4	0.0	3.4	0.0
Less deflection required/Good for short distances	3.2	3.2	0.0	3.2	0.0
More control over drag	3.2	3.2	0.0	3.2	0.0
Inexpensive yarder required	3.2	3.2	0.0	3.2	0.0
Safe	3.2	3.2	0.0	3.2	0.0
Light rigging	3.0	3.0	0.0	3.0	0.0
Less hp required/More pulling strength	2.4	2.4	0.0	2.4	0.0

Table 3.15: Disadvantages associated with Running Skyline (Scab or Grabinski).

	Round 1	Round 2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Brake wear/Pulling against self/Tail pull	3.4	3.4	0.0	3.4	0.0
Lateral yarding	3.4	3.4	0.0	3.4	0.0
Lack of lift/need good deflection/need tall tower	3.2	3.2	0.0	3.2	0.0
Rope wear & tangle/Gear break	3.0	3.0	0.0	3.0	0.0
Short distances/Terrain limited	3.0	3.0	0.0	3.0	0.0
Fuel consumption	3.0	3.0	0.0	3.0	0.0
Drag gravitation on side slopes	3.0	3.0	0.0	3.0	0.0
Productivity/Smaller Payloads/More hp required	2.6	2.6	0.0	2.6	0.0
Soil disturbance	2.6	2.6	0.0	2.6	0.0
Lots of line shifts/Line shift time without mobile tail	2.6	2.6	0.0	2.6	0.0

3.3.6.3 North Bend

The most commonly used rigging configurations was North Bend, which is preferred because of its versatility and ability to lateral yard due to bridling. Like Scab it provides more lift and control of the drag compared to Highlead, while still being simple to setup and operate. The standing skyline provides the ability to yard large payloads and can be productive (

Table 3.16). The expert panel agreed that the greatest disadvantage was amount of time required to shift the skyline, which often results in the temptation to bridle too far (Table 3.17). Bridling too far out the skyline can be slow due to difficulty landing the rigging and can also create higher tensions, which increase rope wear and pose an overloading hazard. Generally a more expensive thee drum yarder is required which takes longer to setup and can cost more to operate. Also in certain uphill setting with limited landing space it can be difficult to land the logs because weight of the haulback pulls the logs away from the yarder.

Table 3.16: Advantages associated with North Bend.

	Round 1	Round 2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Bridling capability/Lateral yarding/Versatility	3.8	3.8	0.0	3.8	0.0
Productivity/Good payloads	3.6	3.6	0.0	3.6	0.0
Increased lift/Less soil disturbance	3.2	3.2	0.0	3.2	0.0
Easy setup and rope shifts/Simple to operate	3.2	3.2	0.0	3.2	0.0
Robust/Hard to break/Easy on machine & ropes	3.0	3.0	0.0	3.0	0.0
Good control over drag/Getting around obstacles	3.0	3.0	0.0	3.0	0.0
Less hp required	3.0	3.0	0.0	3.0	0.0
Good for long distances	2.8	2.8	0.0	2.8	0.0
Fuel consumption	2.6	2.6	0.0	2.6	0.0
Good for downhill yarding	2.6	2.6	0.0	2.6	0.0
Easy on breakerouts	2.4	2.4	0.0	2.4	0.0

Table 3.17: Disadvantages associated with North Bend.

	Round 1	Round 2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Longer skyline shifts/Tempted to bridle too far	3.4	3.4	0.0	3.4	0.0
Overloading hazard/Pull out stumps	3.0	3.2	0.2	3.2	0.0
Need more expensive (3 drum) hauler	3.2	3.2	0.0	3.2	0.0
Longer setup/Cost of operation	3.0	2.8	-0.2	3.0	0.2
Rope wear	3.0	3.0	0.0	3.0	0.0
Long distance yarding	2.8	3.0	0.2	3.0	0.0
Landing and unhooking	3.0	3.0	0.0	3.0	0.0
Hard to drop gear to right location for hook-up	2.8	2.8	0.0	2.8	0.0
Walk in & out for breaker outs	2.8	2.8	0.0	2.8	0.0
Fuel use	2.8	2.8	0.0	2.8	0.0
Lack of skill	2.6	2.6	0.0	2.6	0.0
Suspension/Less control over drag/Breakage	2.6	2.4	-0.2	2.4	0.0
Rider block and fall block hit together	2.4	2.4	0.0	2.4	0.0
Blind leads/Deep gullies	2.2	2.2	0.0	2.2	0.0
Production	2.2	2.0	-0.2	2.0	0.0

3.3.6.4 Shotgun

Another one of the most commonly used configurations was live skyline with a Shotgun carriage. The expert panel strongly agreed that Shotgun can be very simple and cheap to operate because little fuel is used, since gravity return of the carriage requires minimal power from the yarder (Table 3.18). The speed of the gravity outhaul increases with chord slope and is often much faster than outhaul requiring the haulback rope, which makes cycles quick and productive. The live skyline tends to maximize deflection and payloads, while in some cases provides the ability for full suspension during inhaul. However, the configuration is also limited to terrain where you have a steep enough chord slope for gravity to outhaul the carriage (>20%) and usually the front face of a canyon otherwise the additional haulback rope is required for outhaul and to reach the opposing side of the canyon. Shotgun is similar to Scab and Highlead in its limited ability to lateral yard, thus requiring more frequent skyline shifts. Although the concept is simple there is a hazard of overloading the skyline due to the raising and lowering of the skyline each cycle which can contribute to excessive brake, rope and gear wear. Therefore, one needs to operate with caution and should ensure that strong anchors are used. Fouled drags can be difficult to get unstuck since the carriage cannot be pulled in reverse without the haulback (Table 3.19).

Table 3.18: Advantages associated with Shotgun.

	Round 1	Round 2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Fuel use/Cheap to run	4.0	4.0	0.0	4.0	0.0
Productivity/Quick	4.0	4.0	0.0	4.0	0.0
Easy setup/Simple to operate	4.0	4.0	0.0	4.0	0.0
Maximizes deflection & payloads/Full suspension	3.8	3.8	0.0	3.8	0.0
Easy on breaker outs/Easy to land logs & drop gear	3.8	3.8	0.0	3.8	0.0
Less rope/Gear wear	3.8	3.8	0.0	3.8	0.0
Easy to land logs	3.6	3.8	0.2	3.8	0.0
Less hp required	3.2	3.2	0.0	3.2	0.0

Table 3.19: Disadvantages associated with Shotgun.

Response	Round 1 Avg. Rank	Round 2 Avg. Rank	Change	Round 3 Avg. Rank	Change
Limited to terrain/Need slackline for back face	3.6	3.6	0.0	3.6	0.0
Need good anchors	3.4	3.4	0.0	3.4	0.0
Hard to get caught drags unstuck	3.2	3.2	0.0	3.2	0.0
Lateral yarding	3.2	3.2	0.0	3.2	0.0
Brake, rope, & gear wear	1.8	1.8	0.0	2.0	0.2
Complicated/Harder line shifts	2.0	2.0	0.0	2.0	0.0
Overloading hazard/comm. with breaker outs	1.8	1.8	0.0	1.8	0.0
Deflection/Soil disturbance	1.6	1.6	0.0	1.6	0.0
Fuel use	1.4	1.4	0.0	1.4	0.0
Productivity	1.2	1.2	0.0	1.2	0.0

3.3.6.5 South Bend

South Bend is one of the less common configurations used in New Zealand but functions quite similarly to North Bend, and coincidentally has similar advantages and disadvantages (Table 3.20; Table 3.21). The amount of lift generated and the ability to bridle and/or have good control of the drag around obstacles are the configuration's main advantages. However extra gear and rope are required and mainline wear due to lifting of the fall block all result in higher costs. Operators find landing the gear to be difficult in the same way as North Bend due to the arc that the fall block travels when lowered. Lack of experience and skills due to the configuration's limited use are also of concern.

Table 3.20: Advantages associated with South Bend.

	Round 1	Round 2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
More lift	3.6	3.6	0.0	3.6	0.0
Good for getting around rocks and over creeks	3.6	3.6	0.0	3.6	0.0
Ability to pull 90 deg from skyline	3.6	3.6	0.0	3.6	0.0
Less hp required/more break out power	3.4	3.4	0.0	3.4	0.0
Good control of drag	3.2	3.2	0.0	3.2	0.0
Bridling	3.0	3.0	0.0	3.0	0.0
Less weight on tailrope/easy on ropes	2.8	3.0	0.2	3.0	0.0
Production/fast/high line speed	2.6	2.6	0.0	2.6	0.0

Table 3.21: Disadvantages associated with South Bend.

Response	Round 1 Avg. Rank	Round 2 Avg. Rank	Change	Round 3 Avg. Rank	Change
Rope wear/tangle	3.2	3.2	0.0	3.2	0.0
Higher costs/Extra gear & rope needed	3.2	3.2	0.0	3.2	0.0
Need secure anchors	2.6	3.2	0.6	3.2	0.0
Hard to land gear/drop fall block/land logs	3.0	3.0	0.0	3.0	0.0
Knowledge/experience and skill	3.0	3.0	0.0	3.0	0.0
Longer setup/lines shifts	2.6	2.6	0.0	2.6	0.0
Work in bight	2.2	2.6	0.4	2.6	0.0
Slow rope speed/longer outhaul	2.4	2.4	0.0	2.4	0.0
Double purchase	2.0	2.0	0.0	2.0	0.0

3.3.6.6 Motorized Carriages

Motorized carriages are highly regarded as having great versatility as previously mentioned, which bolster many of the configurations associated advantages (Table 3.22). Good lift and control of the drag, as well as its ability to lateral yard and navigate around or over obstacles are highly regarded. High associated productivity and fuel saving when Shotgunning make motorized carriages very attractive. However, many cannot justify the high capital investment in such a carriage, and are not willing to take on extra maintenance, skyline damage due to clamping, or the risk of dropping the carriage. Problems similar to live skyline with the hazard of overloading and the need for secure anchors are also perceived disadvantages (Table 3.23).

Table 3.22: Advantages associated with motorized carriages.

	Round 1	Round 2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Less line shifts/wide corridors	3.6	3.6	0.0	3.6	0.0
Quick/ productive	3.6	3.6	0.0	3.6	0.0
Lateral yarding	3.6	3.6	0.0	3.6	0.0
Lift/ Full suspension	3.4	3.4	0.0	3.4	0.0
Good getting around obstacles	3.4	3.4	0.0	3.4	0.0
Good control of drag/less breakage	3.4	3.4	0.0	3.4	0.0
Fuel savings/ shotgunning capability	3.4	3.4	0.0	3.4	0.0
Easy on yarder/crew	2.8	2.8	0.0	2.8	0.0
Safe	2.8	2.8	0.0	2.8	0.0
Pre stropping	2.4	2.4	0.0	2.4	0.0
Large payloads	2.4	2.2	-0.2	2.2	0.0

Table 3.23: Disadvantages associated with motorized carriages.

Response	Round 1 Avg. Rank	Round 2 Avg. Rank	Change	Round 3 Avg. Rank	Change
Need good deflection/terrain limited	3.4	3.6	0.2	3.6	0.0
Maintenance	3.4	3.4	0.0	3.4	0.0
Drop carriage	3.4	3.4	0.0	3.4	0.0
Clamping damage, rope wear	3.4	3.4	0.0	3.4	0.0
Need strong anchors	3.4	3.4	0.0	3.4	0.0
Expensive	3.0	3.2	0.2	3.2	0.0
Need experienced operator	3.0	3.0	0.0	3.0	0.0
Heavy	2.8	2.8	0.0	2.8	0.0
Noisy	2.6	2.6	0.0	2.6	0.0
Smaller payloads	2.4	2.4	0.0	2.4	0.0
More work for breakerouts	2.0	2.2	0.2	2.2	0.0
Longer haul distances	2.4	2.2	-0.2	2.2	0.0
Slow	1.8	1.8	0.0	1.8	0.0
Harder/longer line shifts	2.0	1.8	-0.2	1.8	0.0

3.3.6.7 *Mechanical carriages*

Mechanical carriages have very limited use in New Zealand operations as previously discussed. However, these carriages have many associated advantages similar to motorized carriages with their versatility, potential fuel savings, and relatively high level of production. They are favored over motorized carriages when it comes to simplicity, maintenance, robustness, and purchase price (Table 3.24). Perhaps they are less often used because of crews lack of experience and the fact that they are only suited to yarders with 3 or more drums. Issues with excessive rope wear and line twist are of concern. It should also be noted that the configurations doesn’t work well for downhill yarding, and lateral yarding can be limited by the length of the drop line (Table 3.25).

Table 3.24: Advantages associated with mechanical carriages.

Response	Round 1 Avg. Rank	Round 2 Avg. Rank	Change	Round 3 Avg. Rank	Change
Less line shifts/wider corridors	3.4	3.4	0.0	3.4	0.0
Lateral yarding ability	3.4	3.4	0.0	3.4	0.0
Good around obstacles	3.4	3.4	0.0	3.4	0.0
Cheap	3.4	3.4	0.0	3.4	0.0
Robust	3.4	3.4	0.0	3.4	0.0
No engine Maintenance/light weight	3.4	3.4	0.0	3.4	0.0
Productive	3.2	3.2	0.0	3.2	0.0
Works good uphill or flat ground/Versatile	3.2	3.2	0.0	3.2	0.0
Drag follows ground	3.2	3.2	0.0	3.2	0.0
Simple	3.0	3.0	0.0	3.0	0.0
Fuel savings	3.0	3.0	0.0	3.0	0.0
Easy for breakerouts	3.0	3.0	0.0	3.0	0.0
Safe	3.0	3.0	0.0	3.0	0.0
Larger Payloads	2.6	2.6	0.0	2.6	0.0

Table 3.25: Disadvantages associated with mechanical carriages.

Response	Round 1 Avg. Rank	Round 2 Avg. Rank	Change	Round 3 Avg. Rank	Change
Need more drums	3.4	3.4	0.0	3.4	0.0
Line twist	3.2	3.2	0.0	3.2	0.0
Rope wear	3.0	3.0	0.0	3.0	0.0
More skills/experience needed	3.0	3.0	0.0	3.0	0.0
Not good downhill	3.0	3.0	0.0	3.0	0.0
Lateral yarding limited by drop line	2.8	3.0	0.2	3.0	0.0
Need water cooled tag line	2.6	2.6	0.0	2.6	0.0
Maintenance	2.4	2.4	0.0	2.4	0.0
Hard on breakerouts	2.4	2.4	0.0	2.4	0.0
Terrain limited	2.4	2.4	0.0	2.4	0.0
Mechanical reliability	2.4	2.4	0.0	2.4	0.0
Longer/complex setup	2.2	2.2	0.0	2.2	0.0
Expensive	2.0	2.0	0.0	2.0	0.0
Eye wear	2.0	2.0	0.0	2.0	0.0
Outdated	1.6	1.6	0.0	1.6	0.0

3.3.6.8 Grapple

The use of a grapple in New Zealand has been somewhat dependent on the owner ship of a swing yarder. With 25% of crews or less using them in the last 5 years they are not widely used, but this is expected to change in the future with the increase of imported used swing yarders and the manufacturing of new swing yarders within the country. Individuals who use grapples note that they have fast cycle times and are therefore productive. They are relatively simple and easy to setup, and are good for short distances. Perhaps an edge that grapples have over other configurations is in the category of safety, since no breakerout is required; there is no man at risk on the cutover. This also means that less man power or a smaller crew size is needed (Table 3.26). However, having fewer crew members can also be a disadvantage when it comes to logistics and mechanical breakdowns. If the yarder operator doesn't have good vision of the logs a spotter is required and needs to communicate effectively with the operator. Other disadvantages include rope wear, the amount of line shifts due to the inability to lateral yard, and that it's limited to shorter haul distances and terrain types (i.e. concave slopes); (Table 3.27).

Table 3.26: Advantages associated with Grappling.

	Round 1	Round 2		Round 3	
Response	**Avg. Rank**	**Avg. Rank**	**Change**	**Avg. Rank**	**Change**
Less man power	3.8	3.8	0.0	3.8	0.0
Safety	3.8	3.8	0.0	3.8	0.0
Good for short distances	3.8	3.8	0.0	3.8	0.0
Unhooking	3.8	3.8	0.0	3.8	0.0
Productive/quick	3.6	3.6	0.0	3.6	0.0
Robust	3.6	3.6	0.0	3.6	0.0
Easy setup	3.4	3.4	0.0	3.4	0.0
Low maintenance	3.0	2.8	-0.2	2.8	0.0

Table 3.27: Disadvantages associated with Grappling.

Response	Round 1 Avg. Rank	Round 2 Avg. Rank	Change	Round 3 Avg. Rank	Change
Need good communication/vision/spotter	3.2	3.2	0.0	3.2	0.0
Rope wear	3.2	3.2	0.0	3.2	0.0
More line shifts	3.2	3.2	0.0	3.2	0.0
Best suited for swing yarders	3.4	3.4	0.0	3.2	-0.2
Limited to short haul distances	3.0	3.0	0.0	3.0	0.0
Terrain limited	3.0	3.0	0.0	3.0	0.0
Narrow corridor	3.0	3.0	0.0	3.0	0.0
Fuel use	3.0	3.0	0.0	3.0	0.0
Maintenance	2.6	2.6	0.0	2.6	0.0
Piece size dependent	2.6	2.6	0.0	2.6	0.0
Need Bunching	2.6	2.6	0.0	2.6	0.0
Log damage	2.6	2.6	0.0	2.6	0.0
Difficult to operate	2.4	2.4	0.0	2.4	0.0
Mechanical reliability	2.6	2.4	-0.2	2.4	0.0
Smaller payloads/less production	2.2	2.2	0.0	2.2	0.0

Table 3.27 (Continued)

No breakerout	2.6	2.0	-0.6	2.0	0.0
Longer setup	2.2	1.8	-0.4	1.8	0.0

3.4 Conclusion

This study discussed the responses and opinions of 50 individuals practicing cable yarding in New Zealand at a professional level, with the validity assured by a panel of 5 experts using the Delphi process. The most widely used rigging configuration was North Bend followed by Running Skyline (scab), Shotgun, and Highlead. Less than 30% of participants use other configurations outside of these four in the last five years. More than half of individuals interviewed stated they had no or limited knowledge with mechanical carriages, and 40% or more said they also had no or limited knowledge with Dutchman and South Bend.

Although there appears to be dependence on a few common configurations, most participants were interested in, or recognized the potentials of, other configurations. For example, it was suggested that Scab and other running skyline systems be used for short yarding distances; while North Bend and Shotgun be used for longer yarding distances (> 300 m). For uphill yarding the Shotgun configuration was most preferred and for downhill yarding Scab was highly regarded. When operating in low deflection settings Highlead may be the only feasible option but Scab also works well. While, in medium and high deflection settings Shotgun and motorized carriages were preferred.

The survey indicated a particular interest in motorized carriages which were not widely used, but recognized as having great versatility with their ability to work in higher deflection settings, pull across broken terrain, around obstacles, and across water courses. Swing yarders were also of great interest, yet only 46% of individuals could discuss them in detail. They are also recognized as being versatile and can work on small landing and are commonly paired with grapples. Coupling a swing yarder with a grapple was also of great interest, but 20% say they have no or limited knowledge with grapples and only 20% say they have used one in the last five years.

It’s clear from the results presented, that some configurations are more often used than others, and that there are certain advantages and disadvantages associated with each. The expert panel has done an excellent job validating these comments, and has provided some consensus, clarity, and explanation surrounding these advantages and disadvantages. For example, North Bend was the most often used configurations and has advantages over other configurations in terms of its ability to yard large payloads while being relatively simple to operate. North Bend was found to be versatile in its ability to generate both partial and full suspension and having bridling capability which permits limited lateral yarding. However, caution should be used when operating North Bend, as skyline shifts can be longer compared to other configurations there is often a temptation to bridle too far, which can pose an overloading hazard and the potential to pull anchor stumps. Motorized carriages were recognized for their versatility through their preference in yarding with various operational constraints because, they provide good control of drags, can fully suspend loads, can lateral yard, and are very quick and productive especially with their ability to be Shotgunned (i.e. gravity outhauled). However, motorized carriages are not widely used because they are limited to settings with good deflection. They are also limited in use because of their high associated cost, increased maintenance compared to non-motorized/slack pulling carriages, rope wear due to clamps, risk of overloading skyline and anchors and the fear of the crew accidentally dropping the carriage. Mechanical slack pulling carriages were not widely used in New Zealand put provide similar advantages to motorized carriages but are less expensive and simple by comparison. Perhaps, they are not used more often because they are often used on swing yarders or modern tower yarders with three or more drums and due to high associated rope wear and wrap issues. Grapples were less used than other configurations, most likely because mechanical grapples were exclusive to use on swing yarders which provide the interlock capability essential for control. Mechanical grapples have high associated rope wear and have been known to be somewhat terrain limited (convex terrain) and preferred over short distances, requiring good vision or communication to grapple logs and frequent line shifts. However, the use of grapples is seen as advantageous because of the reduction in necessary man power and improved safety due to breakerouts not being required, while being quick and productive especially over short distances.

The complexity of operational issues involved with cable logging operations and the versatility of certain configurations create a wide overlap of application between systems. In order to guide practitioners towards which system or configuration might be most applicable given their harvest setting; future research should compare and analyze configurations based on a combination of some of the variables and criteria mentioned in this study. Additionally effort should be placed on the creation of a guide book for selecting rigging configurations, and/or updating national literature used for training with results from this study and future research projects.

Chapter 4: Modelling Dynamic Skyline Tensions in Rigging Configurations: North Bend, South Bend, and Block in the Bight Case Studies

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Harrill, H., and R. Visser. 2013. Simulating skyline tensions of rigging configurations. Future Forests Research Ltd. (FFR). HTN05-12. 8.

4.1 Introduction

The importance of cable tension and research carried out measuring cable tensions are presented in Chapter 3.

Very few studies with the exception of Kellogg (1987) have tried to compare various rigging configurations in the same operating conditions. Static tensions in logging cables, and how to calculate them, has been described by various authors. For example Woodruff (1984) developed a computer program to analyze static tensions for comparison between the Fall Block configurations: North Bend, South Bend, and Modified North Bend. The industry uses a safety factor of three in their engineering designs when calculating the payload potential for logging skylines (Studier and Binkley 1974). This provides room for dynamic forces, sometimes called shock loading that can often send temporary fluctuations in stored elastic energy through the system (Pyles et al. 1994; Visser 1998; Womack 1994). These dynamic forces can sometimes be as much or greater than the payload itself, and if not accounted for through the safety factor, could lead to a skyline failure and potential injury to workers. Very little work has been completed in the monitoring of dynamic forces in cable logging and none have aimed to compare these tensions between rigging configurations. This study aims to compare the observed skyline tensions using a model yarder, by simulating common situations known to cause shock loading. The goal is to provide suggestions on to how to minimize these forces in everyday practice and which configuration to use in varying conditions.

4.2 Objectives

The objectives of this study were to quantify the skyline tensions due to dynamic (i.e. shock) loading for each of the Fall Block rigging configurations when:

1. The load suddenly drops into full suspension.
2. The load collides with a ground object.
3. Bridling to reach stems away from the skyline corridor.
    a. During breakout.
    b. While lateral yarding

4.3 Methods

4.3.1 Equipment

All simulated yarding tests were performed using the 1:15 scale University of Canterbury's School of Forestry Model Yarder (Figure 1). The yarder was custom built, including a 2m adjustable spar, with electric variable speed motor, and a four drum winch set (Table 4.1). The synthetic ropes originally manufactured for yachting range in diameters from skyline (4mm) to main line and haulback (3mm) and tagline (2mm), and were supplied from Nautilus Braids Co. in Lincoln, New Zealand.

Table 4.1: UC Model Yarder and setup specifications used during simulated yarding tests.

Description	Value	Units
Tower height	2.32	m
Tail height	2.05	m
Span	12.0	m
Deflection	1.2	m
Deflection	10	%
Skyline diameter	4.0	mm
Skyline weight	0.014	kg/m
Mainline diameter	3.0	mm
Mainline weight	0.006	kg/m
Haulback diameter	3.0	mm
Haulback weight	0.006	kg/m
Carriage weight	0.229	kg
Fall block weight	0.137	kg
Butt Rigging and Chokers	0.036	kg
Log weight	4.92	kg

Skyline tensions were measured with the use of a PT Global PT1000 Single Point load cell and custom built mounting bracket along with a PT200M display unit (Figure 4.1). The display unit was connected to a laptop computer which recorded skyline tensions to the nearest gram continuously at 20 reading per second, using PT Program Viewer 200 software[4]. The laptop computer also recorded video of operation and line tension simultaneously using Snagit video capturing software and the laptops built in camera. The video was later used for time study analysis.

Figure 4.1: UC Model yarder and PT Global load cell with custom built mounting bracket and display unit.

4.3.2 Operations Description

Three tests were performed to simulate common causes of shock loading during cable yarding operations (Figure 4.2). Each test was repeated 10 times for each of the three rigging

[4] Programme Viewer Software Version 3.0. PT Global Inc. Auckland, New Zealand.

configurations (e.g. North Bend, South Bend, and Block in the Bight); five of which used long choker lengths (55 mm) and the other five used short choker lengths (32 mm). The same 4.92 kg log was used for every yarding test, and it was positioned in the same starting spot each time. The span was 12m and the spar height and tail hold height were 2.32 and 2.05 m respectively. The haulback tail block was placed directly in line with the skyline at a height of 1.15 m from the ground except during the bridling test. The skyline was set at 10% mid-span loaded deflection for each test, measured using a laser level. The yarders motor was set to the desired speed level (approximately 0.3 m/sec) and audible signals were used to annotate operational procedures. The operator took special effort to control the drag as consistently as possible for each test, in an attempt to minimize variability due to operator.

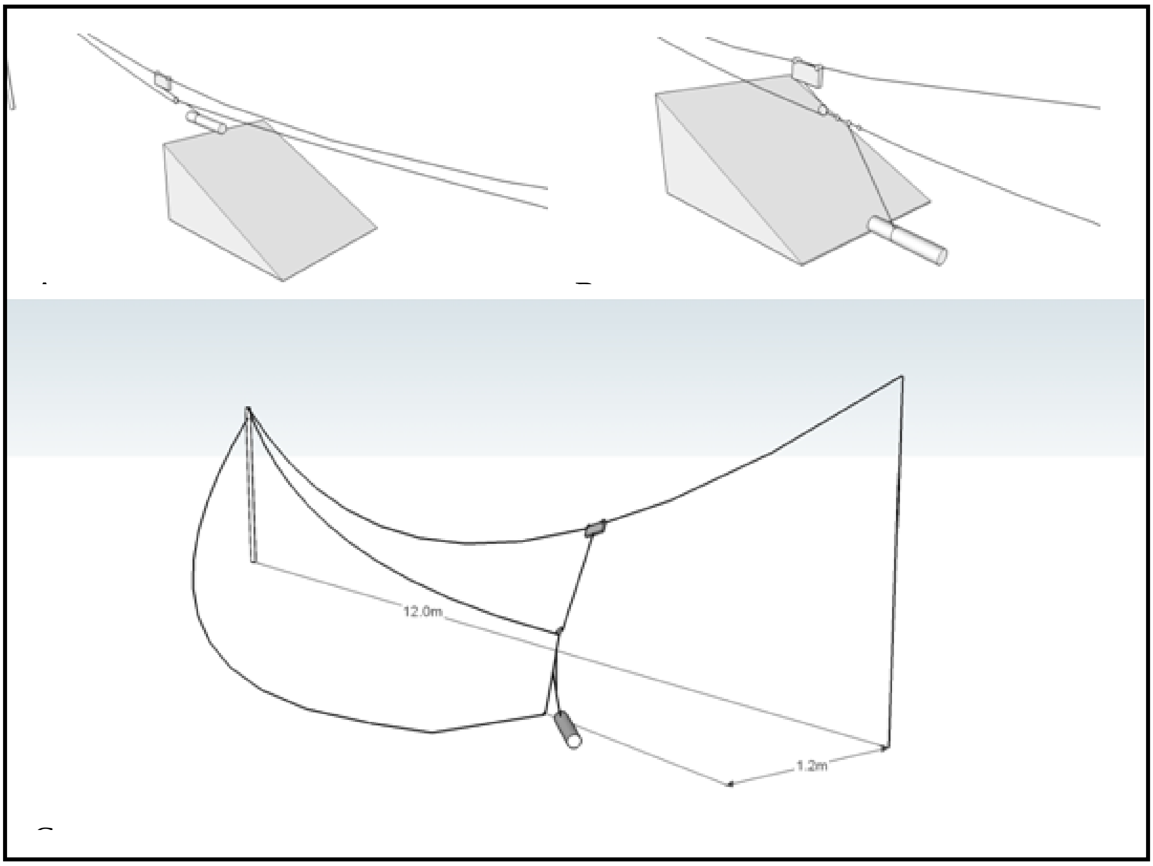


Figure 4.2: Diagram of the three tests performed (A) Drop, (B) Impact, and (C) Bridling.

4.3.3 Drop Test

The drop test (Figure 4.2A) started with the log at mid span (6m) resting on the ground. The main line was pulled in with brake applied to the haulback until slack was taken out of the line and the log began to move. Brake pressure was reduced to the haulback to allow the log to be yarded forward and up the ramp. The log was then pulled over the end of the ramp into full suspension generating a shock load, and then continued along the skyline corridor until it reached the tower, where it was lowered to the ground.

4.3.4 Impact Test

The Impact test (Figure 4.2B) started in the same position as the drop test. The log was then yarded forward 45 cm until it collided with the bottom of the ramp where it initially stopped until slack was pulled out the ropes and enough force was generated to dislodge the log, generating a shock load. The log continued to be yarded to the tower and then lowered the same as in the drop test. The haulback and main ropes were operated in the same manner, only this time less brake pressure was applied to the haulback in order to maintain ground leading of the log to ensure a collision with the ramp edge.

4.3.5 Bridling Test

The bridling test (Figure 4.2C) started with the log resting on the ground at 10.35 m from the tower and offset to one side of the skyline by 1.20 m where it would normally be too far away to reach with either size of chokers, thus requiring the practice of bridling. The tail block was offset 1.20 m from the skyline and placed directly behind the log at ground level. The mainline was pulled in while applying pressure to the haulback brake until partial suspension was generated. Brake pressure was then decreased to allow the log to be yarded laterally back under the skyline corridor, and eventually along the corridor until mid-span where it was lowered to the ground.

4.3.6 Data Analysis

Video recording along with the sound feed of audible signals was used to perform a time study on individual yarding cycles (Figure 4.3). Cycles were broken down into extraction cycle segments: breakout of the log, yarding or lateral yarding, yarding up ramp, full suspension, and lowering the load. The maximum tensions observed during those time segments were recorded into Microsoft Excel spreadsheets to generate graphs and summary statistics. The data was screened for normality and then used to perform a two-way analysis of variance (ANOVA) in Minitab[5].A Tukey test was included for the purpose of making a comparison of maximum tensions between rigging configurations. In all test the null hypothesis was that there was no difference in maximum skyline tension between treatments.

[5] Minitab Version 16.2. Minitab Inc., State College, PA, USA

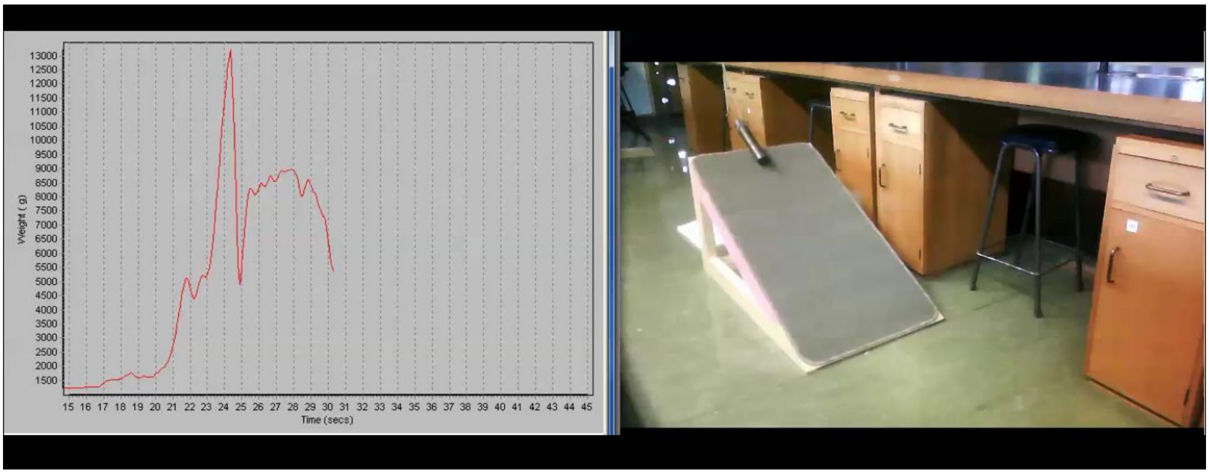


Figure 4.3: Simultaneous video recording of yarding cycle and skyline tension monitoring using Snagit software.

4.4 Results and Discussion

Let us first consider the skyline tension without shock loading, when the carriage and load are fully suspended but stationary and forces have come to equilibrium at mid span. Static skyline tension at mid-span for any operation can be calculated using a very simple equation (WorkSafeBC 2006):

$$T = \frac{L * S}{4D} + \frac{WS^2}{8D}$$

Where T= skyline tension (kg), L= weight (kg) of the load (carriage, logs, and haul back line), S= span length (m), D= deflection (m), W= weight of skyline (kg/m)

Using the above equation for tension and the model yarder specifications from Table 4.1, the calculated static skyline tension at mid span when fully suspended would be 13.51 kg. This is surprisingly close to the measured static skyline tension at mid-span of 13.06 kg. However, the static skyline tension at mid-span differs when the fall block configurations are used. The difference is due to how the load achieves suspension and the function of the cables.

The calculation used in the static tension equation assumes the use of a standing skyline system where the skyline suspends the load and the haul back is used to transport the carriage, whereas to achieve lift with the fall block configurations, brake pressure has to be applied to the haul back while the main line is pulled onto the corresponding drum. The "tug-of-war" between the main line and the haulback eventually results in enough vertical force to lift the log off the ground after which the majority of the load is transferred to the skyline. However, the main line and haul back still share a portion of the load because if the brakes on one or both of these drums were to be released the load would plummet to the ground. The fall block configurations therefore result in decreased skyline tension compared to what was calculated in the static tension equation and that observed.

The actual static skyline tension at mid-span was 10.07 kg, 11.61 kg and 11.76 kg for North Bend, South Bend and Block in the Bight respectively. Dynamic loading was compared to the static tension in terms of its proportional increase. Amplification due to shock loading during breakout of logs in this study will be calculated using an equation from Pyles et al. (1994) for breakout tension amplification:

$$Load\ Amplificaiton\ Factor = \frac{peak\ breakout\ tension - skyline\ pretension}{skyline\ pretension}$$

The above equation can also be used to calculate the amplification of shock loading during drop tests, by substituting the fully suspended static skyline tension for skyline pretension.

Table 4.2: Maximum skyline tensions observed and calculated amplifications during various shock loading tests.

Test	Cycle Component	Configuration	Choker Length	Average (g)	SD (g)	Amplification
Drop	Full Suspension	North Bend	Short	11501	713	1.1
		North Bend	Long	11992	1737	1.2
		South Bend	Short	12923	224	1.1
		South Bend	Long	13845	523	1.2
		Block in the Bight	Short	13053	242	1.1
		Block in the Bight	Long	14032	401	1.2
Impact	In haul	North Bend	Short	10671	3070	7.6
		North Bend	Long	12402	1225	8.8
		South Bend	Short	9010	887	6.2
		South Bend	Long	10833	381	7.1
		Block in the Bight	Short	11482	1643	7.4
		Block in the Bight	Long	10997	822	7.3
Bridling	Breakout	North Bend	Short	4103	887	2.7
		North Bend	Long	7020	2503	5.2
		South Bend	Short	4619	598	3.4
		South Bend	Long	6246	2136	4.7
		Block in the Bight	Short	4740	256	3.1
		Block in the Bight	Long	10231	3791	8.1
Bridling	Lateral yarding	North Bend	Short	11068	699	n/a
		North Bend	Long	12432	528	n/a
		South Bend	Short	11446	595	n/a
		South Bend	Long	14258	2073	n/a
		Block in the Bight	Short	11376	606	n/a
		Block in the Bight	Long	13185	2141	n/a

4.4.1 Drop Test

ANOVA for the drop test indicated that both the variable of choker length and rigging configuration were statistically significant but not the interaction between them, with P-value<0.01 and P-value<0.00; $\alpha = 0.05$ respectively. The maximum tensions were consistent within treatments, with longer chokers generating higher tensions and showed that South Bend behaved quite similar to Block in the Bight (Figure 4.4). North Bend with short chokers produced the lowest recorded average peak skyline tension (11,501 g) and was 1.14 times greater than the static skyline tension at mid-span (Table 4.2). The greatest tension recorded was for Block and the Bight with long chokers (14,032 g) and was 1.19 times greater than the static tension at mid-span. Higher tensions with longer chokers can be explained by the log having to fall further and therefore attain higher velocity (Figure 4.5). South Bend and Block in the Bight may perform similarly but the Tukey test found them to be significantly different from North Bend.

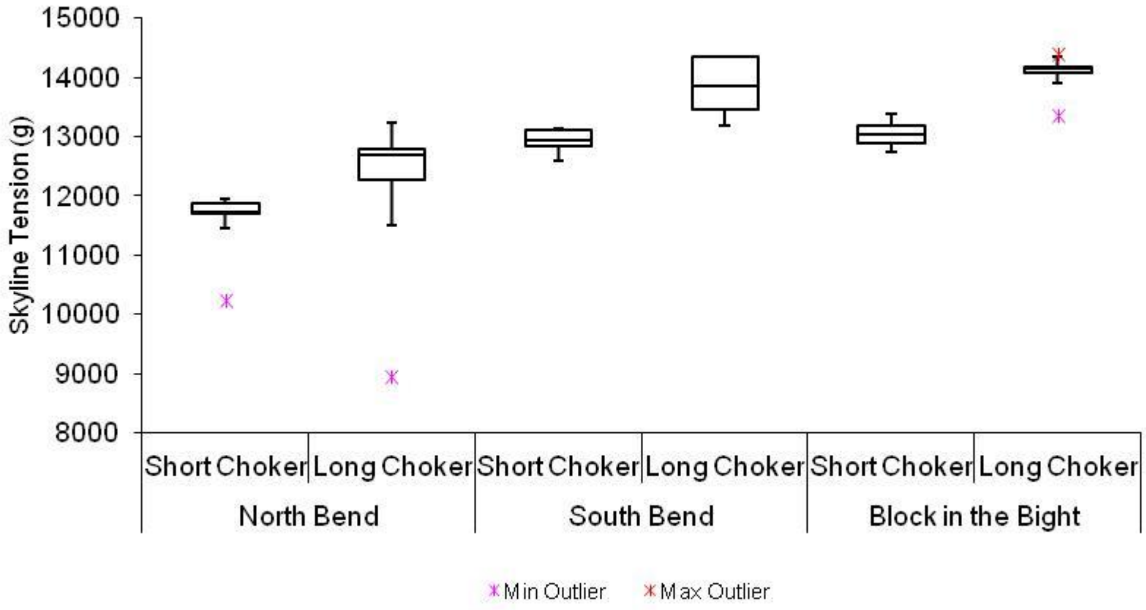


Figure 4.4: Maximum skyline tensions generated during drop test with log in full suspension.

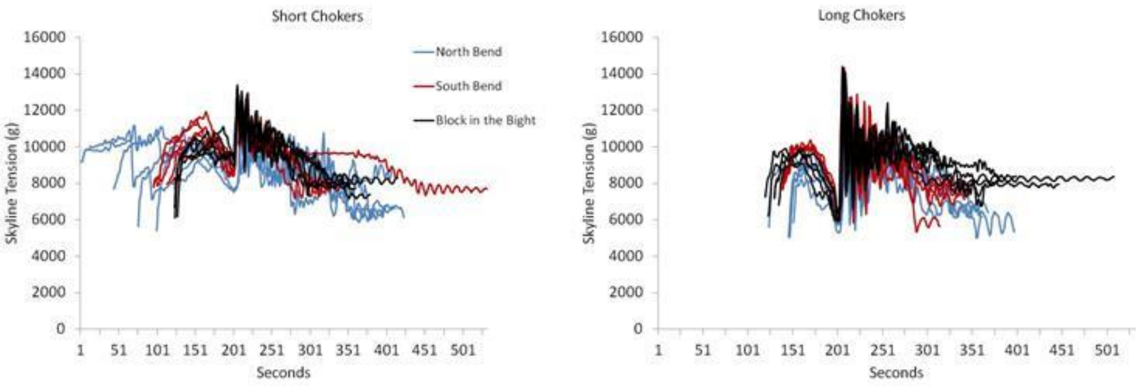


Figure 4.5: Drop test comparison between short and long chokers; log dropped into full suspension at 201 seconds.

4.4.2 Impact Test

ANOVA found no statistical significance in either rigging configuration or choker length for the impact test. What is interesting to note however is how similar tensions were between the long and short chokers when the Block and the Bight rigging configuration was used as compared to others (Figure 4.6; Table 4.2). It's interesting that South Bend with short chokers produced the lowest tensions, which can be attributed in part to the more upward lift generated by the geometry of the main rope and fall block used. It was also observed that this configuration performed very well at avoiding the ground object as several cycles were repeated since the log avoided collision altogether. Woodruff (1984) found that South Bend was introduced one year after North Bend as an alternative for down-hill yarding due to its ability to avoid hang-ups and reduced brake wear to the haulback.

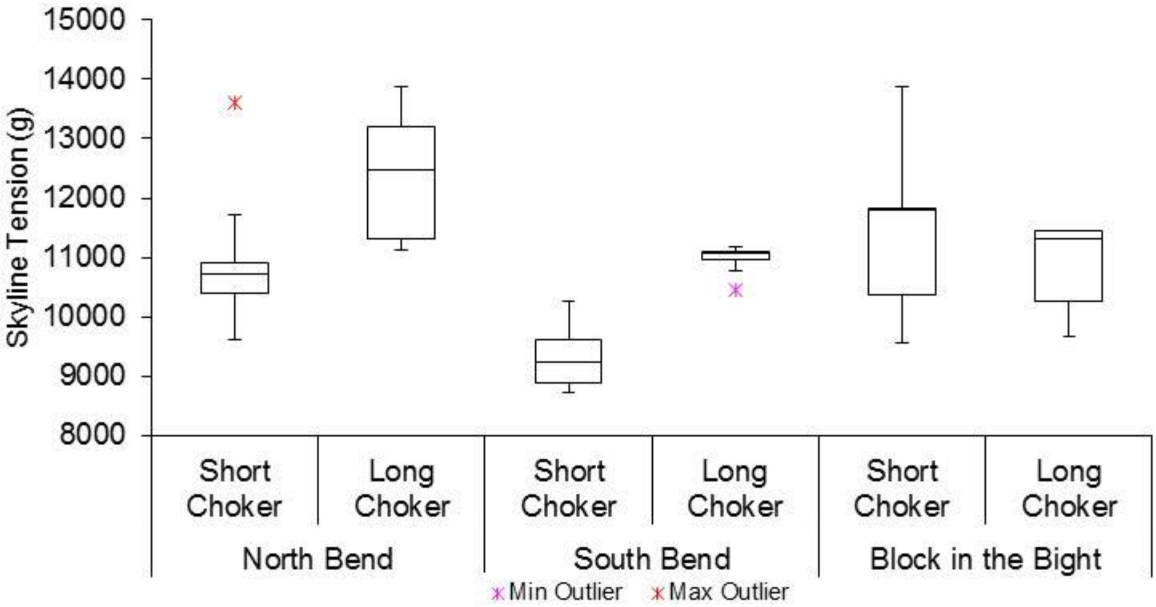


Figure 4.6: Maximum skyline tensions generated when log had collision with ground object.

4.4.3 Bridling Test

During bridling maximum tensions recorded during the initial breakout component of the yarding cycle were somewhat similar with exception of Block in the Bight using long chokers (Figure 4.7; Table 4.2). When long chokers were used, tensions were highly variable (Figure 4.8), especially for Block in the Bight during breakout, which had the greatest average peak tensions for the cycle component (10,231 g). The resulting tension was 87% of static tension at mid-span and 2.2 times greater than observed with short chokers (4,740 g), and highlights the difference in amplification of 8.1 and 3.1 for long and short chokers respectively. The video footage shows the skyline in this setup stretching into view of the camera lens, when configurations did not. This can be somewhat explained by how the mainline had to pull more rope onto the drum than with the short chokers, which put more tension on the mainline and haulback to attain the same amount of desired lift to the log, thus allowing the coefficient of friction to be reduced and allowing the log to move forward. The increased tension in mainline and haulback is partially transferred to the skyline and in this case is exaggerated by the geometry of the mainline and the purchase in the fall block; where the terminal end is connected to the skyline carriage. ANOVA results indicated that only choker length was statistically significant (p-value<0.00, $\alpha = 0.05$).

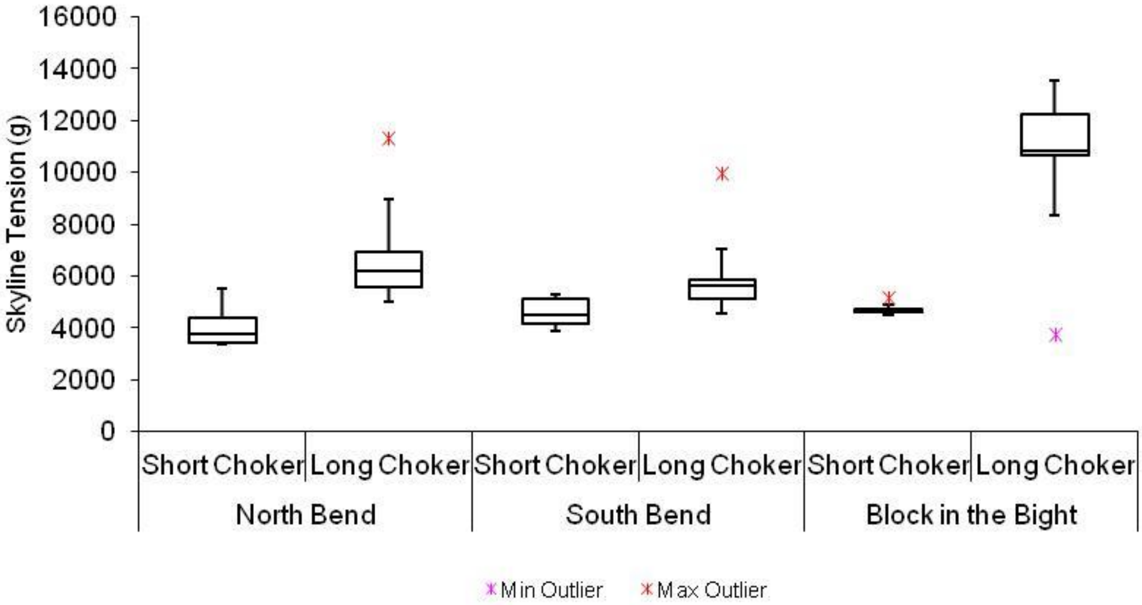


Figure 4.7: Maximum skyline tensions generated during initial breakout while bridling.

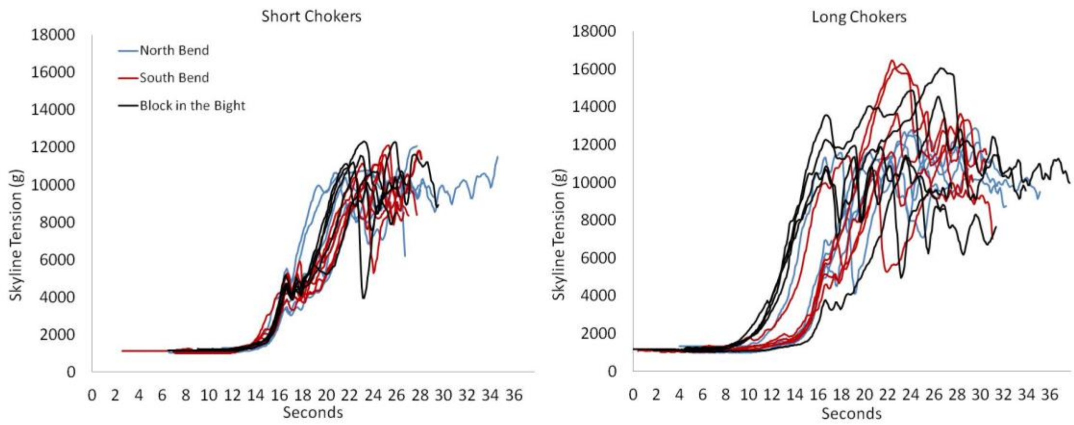


Figure 4.8: Bridling test comparison between short and long chokers.

Once the log was moving during the component of lateral yarding the exacerbated effect of the long choker length on Block in the Bight was reduced. However, choker length was still the only variable to have statistical significance (p-value < 0.00, $\alpha = 0.05$). The longer choker length also produced greater variability in maximum tension, but more so for the South Bend and Block in the Bight configurations (Figure 4.9). This again may be somewhat explained in the geometry of the main rope and fall block, where North Bend does a better job of equalizing the tensions when the fall block runs back and forth on the mainline rather than straight up and down with the double purchase of the others.

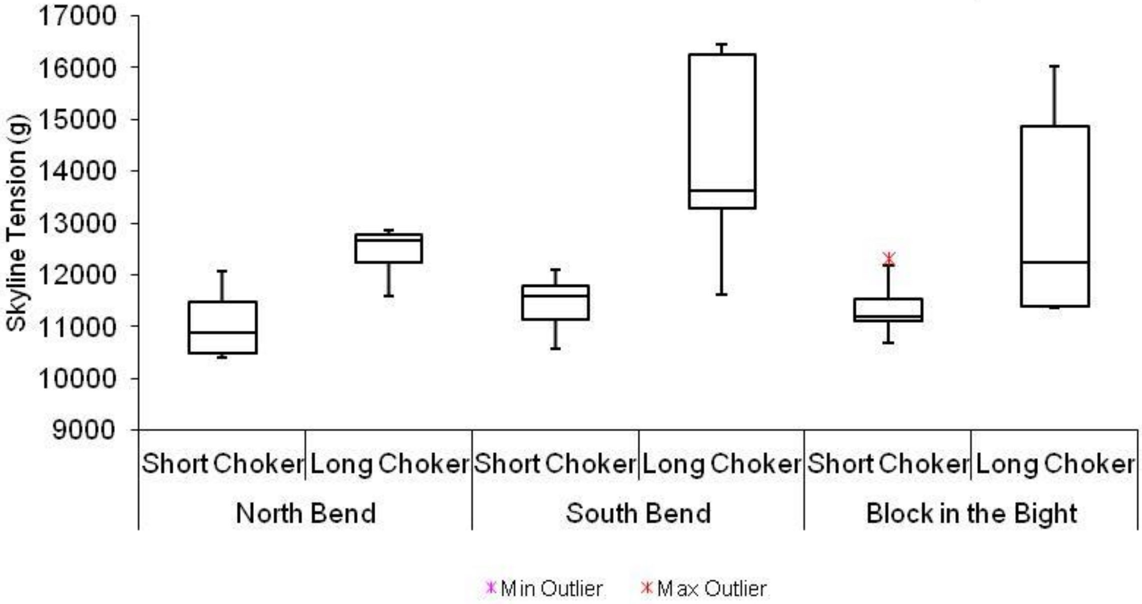


Figure 4.9: Maximum skyline tensions generated during lateral yarding when bridling.

4.5 Conclusion

The study results, using a model yarder, showed that there were differences in skyline tensions between rigging configurations and varying choker length for the same application. However, statistical analysis showed that, in all tests with exception to the drop test, that there was no significant difference in maximum skyline tensions generated based on which rigging configuration was used. There was no significant difference in skyline tension between any of the treatments when the log had a collision with a ground object, although South Bend yielded the smallest tension and performed best in avoiding collision. In both the initial breakout and lateral yarding components of a cycle during bridling, choker length was the only variable found to be statistically significant. Where longer chokers produced higher and more variable skyline tensions especially when using Block in the Bight during breakout, and while lateral yarding with South Bend or Block in the Bight.

Results suggest that in some cases one configuration might be more preferred than another based on potential skyline tension. However, there are other ropes involved in these configurations which are subject to shock loading like the haulback and especially the mainline, and in some occasions the mainline tension can limit the allowable payload. Monitoring tensions on these operating ropes requires a load cell that allows the moving ropes to pass through the device. Monitoring of the mainline and haulback were outside of the scope of this research but warrant further investigation. It is also important to note that tensions and shock loading in this study will differ due to scale issues, especially with respect to rope self-weight. Where a common 28 mm skyline weighs approximately 3.12 kg/m and can account for a large portion of vertical forces, compared to 13.7 g/m used with the model yarder.

4.5.1 Recommendations

- Use North Bend for expected drops into full suspension and where possible shorten choker length.

Results suggest that in some cases one configuration might be more preferred than another based on potential skyline tension. For instance, North Bend proved to be much better in minimizing peak tensions than others during the simulated drop tests. Perhaps choosing North Bend over the other fall block configurations when encountering a sudden drop into full suspension is a good choice, due to the pendulum effect observed that dampens the loading. Using longer chokers during drop tests resulted in tensions that were 1.19 times greater than the static skyline tension at mid-span. If the static tension at mid-span were to be equal to the safe working load of the rope, this could pose a concern, as dynamic tensions would then approach the rope's endurance and elastic limits (50-60% breaking strength).

- South Bend may be an appropriate configuration when risk of collision with ground objects is high.

Although it is not statistically significant, we can see that South Bend performed well in the simulated impact test, resulting in the lowest recorded peak tensions, which confirms the findings of Woodruff (1984) on the historical use of the configuration.

- Use shorter chokers when bridling when possible and avoid the combination of long chokers with Block in the Bight.

Bridling is a common practice to reach logs offset from the skyline. Tests results indicated that using longer chokers which are preferred to reach logs can contribute to larger and more variable tensions during breakout and lateral yarding, and provide less control over the drag. The combination of Block and the Bight and long chokers while bridling produced severe amplifications (8.1 compared to 3.1 for short chokers) of skyline tension and should not be advised.

Chapter 5: Comparing Productivity and Skyline Tensions of Rigging Configurations in New Zealand

5.1 Introduction

5.1.1 Production Research

Cable logging productivity is often the single most important metric used to describe, evaluate or even select an appropriate rigging configuration. Productivity is expressed as volume (m^3) or tons produced per unit of time. Logging operations are usually costed-out by using a combination of fixed and variable costs (Miyata 1980), which covers capital investment, operating and labor (Samset 1985). Therefore, production being the denominator in the equation of cost per unit volume (i.e. $\$/m^3$) plays an important role in the overall economics of a logging operation; hence the importance of quantifying the productive potentials of new equipment and methods (Dykstra 1975, 1976a).

Cost effectiveness is generally improved by two means: either decreasing the associated costs (i.e. inputs) or by increasing the level of production (outputs). Innovation and interest in improving cost effectiveness in recent years has led to a number of new equipment and technology developments in the New Zealand forest industry (Visser et al. 2014). Rates of production and costs are very difficult by nature to estimate in cable logging operations because conditions are often highly variable between and within harvesting sites. This problem is compounded by the variety of equipment and methods, and their combinations referred to as a rigging configuration.

There have been many studies examining productivity of cable logging operations around the world, spanning nearly a century (Samset 1985). However, relatively few have aimed to compare different rigging configurations, especially in similar working conditions; with the exception of Dykstra (1975), Dykstra (1976a), Kellogg (1987) and Forrester (1995). Each comparative study found that a variety of rigging configurations were practical but, one particular configuration was most productive under the conditions studied in logging operations, conditions may change on a monthly, daily or even hourly basis and so do the efficiencies of each configuration. Continued research into the relative efficiencies of rigging configurations is essential if the capabilities and utility of these systems are to advance (Dykstra 1976a; Kellogg 1987). Improving our understanding of the different cable logging methods (i.e. rigging configurations) and new developments by way of comparing their associated operational efficiency could help in the training of crews, planning, implementation and cost effectiveness of cable logging (Samset 1985).

5.1.2 Cable Tensions Research

There was a substantial amount of research conducted into cable logging tensions, mostly through the US Forest Service and Oregon State University (Kendrick 1992). Early investigations aimed to describe forces mathematically so that predictive equations could be developed (Carson and Mann 1971; Lysons and Mann 1967; Sessions 1976). As computing power increased more complex algorithms and computer programs for payload analysis were developed (Carson 1976; Falk 1981; Wilbanks 1985; Woodruff 1984). Dynamic tensions were described by Carson and Jorgensen (1978) and Pyles (1988), noting that static tensions are rarely corroborated in real operations. Further work identified alternative ways that dynamic tensions could be recorded and how to model them (Carson et al. 1982; Kroneberger-Stanton and Hartsough 1992; Lyons 1997; Pyles et al. 1994; Womack 1994). The behavior of some logging systems was investigated by Visser (1998) and Miles et al.

(1993), and tension monitors provided results and benefits to contractors (Hartsough 1993; Smith 1992). As such, most research is related to guylines rather than working ropes and none aimed to compare tensions between configurations.

Targeted case studies included (1) North Bend as the most common New Zealand rigging configuration; (2) standing skyline motorized carriage as a modern rigging configuration with potential to increase productivity, and (3) live skyline motorized grapple carriage configuration being an option to fully mechanize cable operations.

5.2 Objectives

The aim of this study was to provide an analysis of the application of several rigging configurations employed in New Zealand cable logging operations, including their productivity and skyline tensions. The study was designed so that operating conditions were kept as similar as possible between study sites to allow a fair comparison of the configurations studied. The objectives of this study were to:

1. Establish cycle times, payloads and hence productivity for a selected set of rigging configurations.
2. Determine which variables affect the cycle times of rigging configurations.
3. Compare and contrast the differences in production, delays, labor and energy.
4. Quantify the skyline tensions for each rigging configuration.
5. Determine which variables affect the tensions of rigging configurations.
6. Compare and contrast the differences in payload to tension, amplifications and performance characteristics.
7. Identify further research needs in determining the efficiency of cable logging operations.

5.3 Methods

5.3.1 Study Sites

A total of eight different cable logging operations were visited on the North and South island between August, 2013 and February, 2014. The operations were conducted on private, steep terrain forest plantations, representative of typical New Zealand conditions. Each study site was motor-manually felled prior to the start of operations and yarded mature (approx. 25 to 30 years old), full tree length *Pinus radiata* with exception to Study Site 7 where *Pseudotsuga menziesii* was grown. All operations studied utilized either a live or standing skyline system employing one or more rigging configurations across a variety of yarding corridors, all of which used a bulldozer as a mobile tail hold machine (Table 5.1).

Table 5.1: Summary of observed study site and yarding corridor details.

Study Site	Region	Yarder	Yarding System	Configurations	Span (m)	Chord Slope (%)	Deflection (%)	Avg. Yarding Dist. (m)	Piece Size (m^3)
1	Canterbury	Madill 171	Live Skyline	Falcon Slackline	345	-26	6.1	249	1.6
					352	-27	5.9	185	
					364	-27	7.4	244	
2	Nelson	Madill 171	Live Skyline	Falcon Shotgun	316	-47	5.7	221	1.4
					338	-46	5.8	229	
3	Gisborne	BE-85	Standing Skyline	North Bend	940	-14	5.2	280	2.4
				North Bend Bridled	920	-14	5.1	124	
4	Gisborne	Madill 172	Standing Skyline	Acme S28 Slackline	335	-17	4.2	181	2.1
					330	-18	6.1	278	
5	Nelson	Berger C19	Live Skyline	Falcon Shotgun	602	-30	6.1	184	1.6
6	Marlborough	Dispatch-85	Standing Skyline	North Bend Bridled	1100	-43	3.8	311	2.4
7	Nelson	BE-70LT	Standing Skyline	North Bend	395	0	8.4	337	1.2
					398	1	10.1	248	
8	Otago	Madill 071	Standing Skyline	Acme S28 Slackline	284	-20	6.9	230	1.5
				Acme S28 Slackline	296	-21	6.2	191	
				Acme S28 Shotgun	354	-23	6.2	145	

Table 5.2 provides an overview of both the yarder and carriage specifications used at the sites, with only the Madill 171 being used at two different locations. Only the Madill 071 is a medium sized machine, with a 1 inch (25mm) skyline, 14m tower and 202 kW engine rating.

All other machines can be considered to be large tower yarders with 1 1/8th inch (28mm) skyline and > 300kW engine ratings.

Table 5.2: Summary of equipment used during the study of rigging configurations and their specifications.

Yarder Model	Madill 171	BE-85	Madill 172	Berger C19	Dispatch-85	BE-70LT	Madill 071
Rated Engine Power (kW)	335	335	335	391	335	335	212
Tower Height (m)	22	26	22	22	26	21	14
Skyline Diameter (mm)	28.7	28.7	28.7	28.7	28.7	28.7	25.5
Skyline Safe Work Load (tonnes)	21.3	21.3	21.3	21.3	21.3	21.3	18.6
Mainline Diameter (mm)	22.3	19.1	19.1	22.3	25.5	19.1	19.1
Haulback Diameter (mm)	19.1	17.5	19.1	19.1	19.1	17.5	15.9
Carriage Type	Falcon	Fall Block	Acme S28	Falcon	Fall Block	FallBlock	Acme S28
Carriage Weight (kg)	2,200	1,000	860	2,200	1,000	1,000	860
Carriage Engine Power (kW)	43	0	21	43	0	0	21

Each crew was studied for one to two days while they performed work as usual. The research team's goal was to record detailed information for a minimum of 30 yarding cycles using one or more rigging configurations (Figure 5.1-Figure 5.3); (Studier and Binkley 1974). Other parts of the cable logging operations such as processing, loading and trucking were outside the scope of the study.

5.3.1.1 Rigging Configurations

Cable logging operations observed in this study were limited to two skyline systems (i.e. live and standing) and three main configurations (as described in detail by Studier and Binkley (1974)): North Bend, motorized slack pulling carriage, and motorized grapple carriage, with two individual variations of each treated as separate configurations.

5.3.1.2 North Bend

North Bend is the most commonly used configuration in New Zealand (Harrill and Visser 2011). It is very simplistic in that it does not require a sophisticated yarder, and simple non powered carriages can be used. The configuration is classified as a standing skyline system, and requires a skyline, mainline, and haulback line (Studier and Binkley 1974). The configuration uses the haulback line to return the carriage and butt-rigging to the log location, and pulls the payload of logs back to the landing with the mainline. The configuration is unique compared to other standing skyline systems in that it uses a fall block that the mainline passes through to generate lift, via tensioning the haulback and the mainline simultaneously (Figure 5.1). The main advantage of the configuration is that it is very simplistic and easy to operate. In addition it has some versatility in different terrain and settings, and can even yard logs lateral to the skyline through a slight variation of the configuration called North Bend Bridled (Harrill and Visser 2012). In some cases to achieve lateral yarding, the haulback blocks are offset perpendicular to the skyline rather than directly under the skyline. The offsetting of haulback blocks is referred to North Bend Bridled.

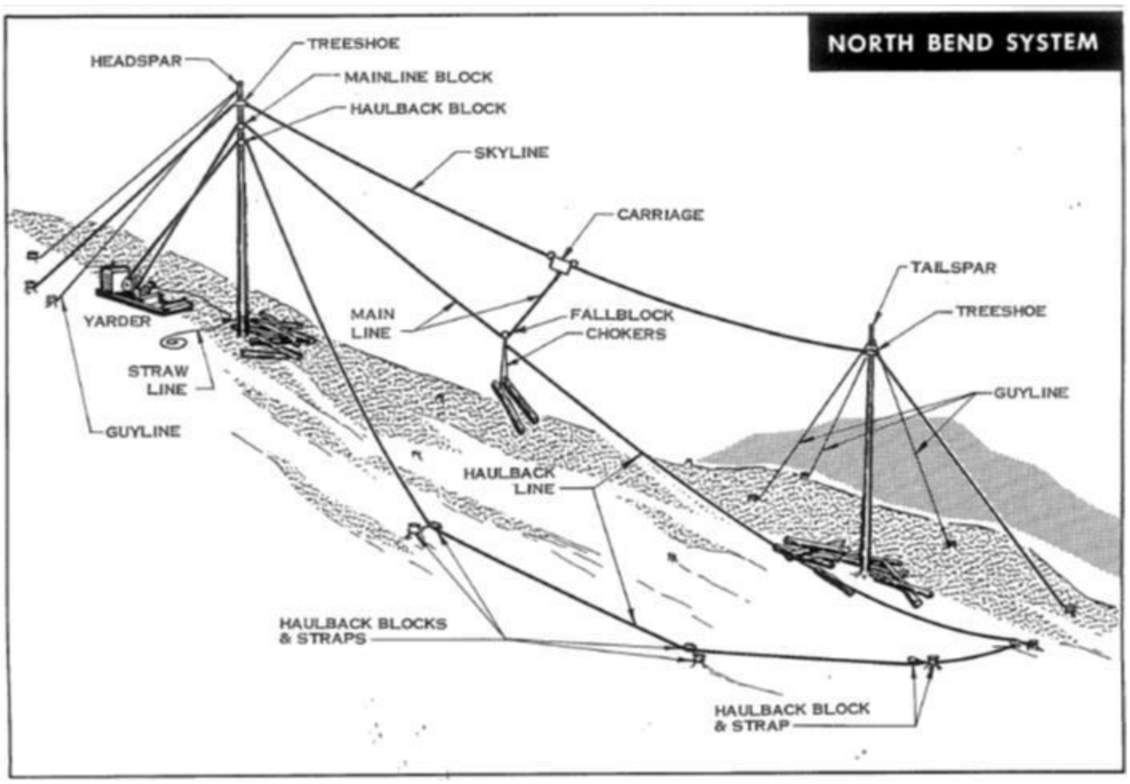


Figure 5.1: Standing skyline operating the North Bend rigging configuration (Studier and Binkley 1974).

5.3.1.3 Acme Motorized Carriages

Motorized carriages were not a popular rigging configuration in New Zealand (as found in the 2011 survey), but are gaining popularity due to their versatility in a wide range of operating conditions (Harrill and Visser 2012). An Acme motorized carriage has an internal motor used to pull the mainline through the carriage, so that the breaker-outs can easily carry the cable and chokers to the logs. One of their main advantages is that they are very good at lateral yarding due to their slack pulling capability and control when extracting logs. The motorized carriage is usually operated as a standing skyline system and can be operated either in the Shotgun or Slackline configuration. In the Shotgun configuration the carriage is outhauled by gravity along the skyline, and the mainline is used to pull the carriage to the landing. Where the chord slope of the skyline is not adequate (< 20%) or logs must be pulled from the opposing side of a valley, the carriage may be used in the Slackline configuration. In the Slackline configuration a haulback is attached to the back of the carriage to facilitate outhaul. The disadvantage of the motorized carriage compared to North Bend type carriages is the high associated cost, and the risk of damaging the carriage if it collides with the ground or logs. The motorized carriages in the study sites were all Acme carriages, and referred to as such.

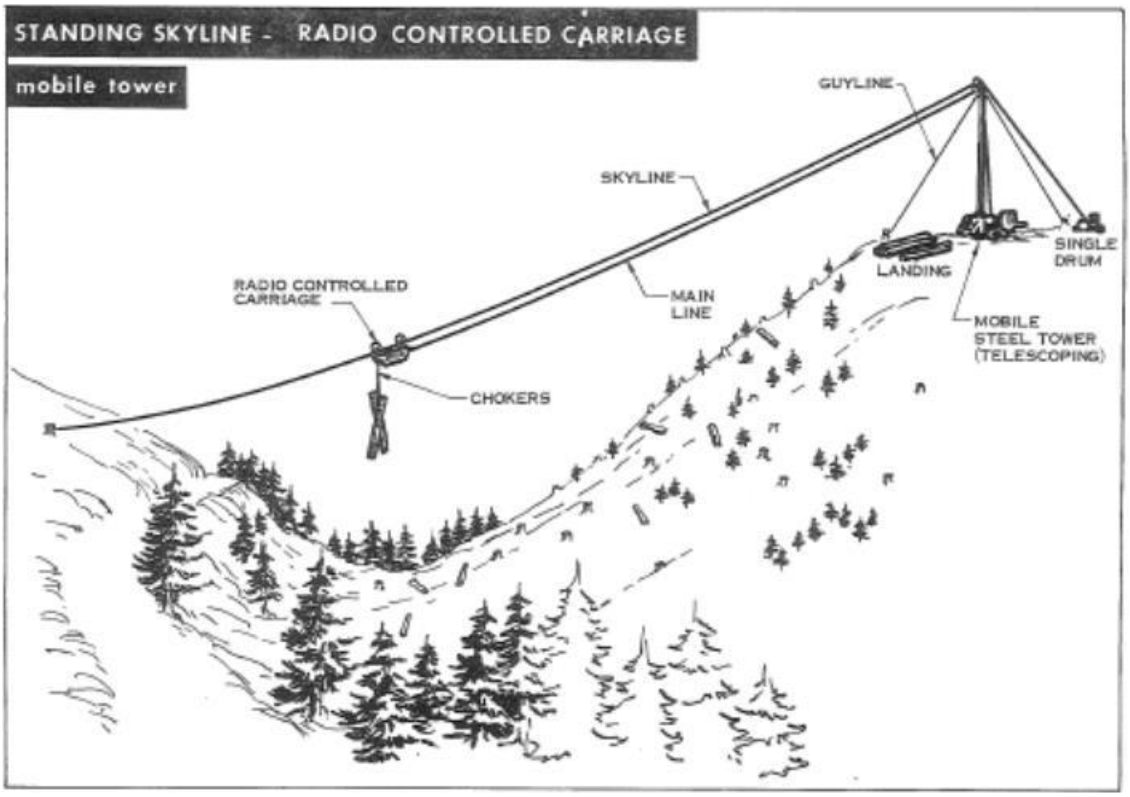


Figure 5.2: Standing skyline with radio-controlled Acme S28 motorized carriage in the Shotgun configuration (Studier and Binkley 1974).

5.3.1.4 Falcon Motorized Grapple Carriage

Mechanical grapple carriages are not widely used in New Zealand except on the relatively new swing yarders which employ a running skyline system (Harrill and Visser 2012). The grapple is opened and closed by altering the lengths of the three cables used in the running skyline system. When mechanical grapples are used they have been found to be productive and cost effective, since they do not require choker-setters to attach chokers to logs, but are limited to short distances (<200 m); (Studier and Binkley 1974). One recent New Zealand innovation is the Falcon Forestry Claw (Falcon) motorized grapple carriage, which has an internal motor which opens, closes and rotates the grapple. This type of carriage simplifies the cables required as they do not need to control the grapple and makes the concept of grappling extendable to a wide range of yarders and extended distances. Since the motorized grapple configuration does not have the ability to pull slack, it must be employed on a live skyline system, where the skyline is raised and lowered during each cycle to reach the logs on the ground. Just like the other motorized carriages (e.g. Acme) it can be operated in the Shotgun or Slackline configuration. While this versatility is an advantage, a disadvantage is the capital cost (approximately NZ$130,000) and there is a risk of damage if it is dropped.

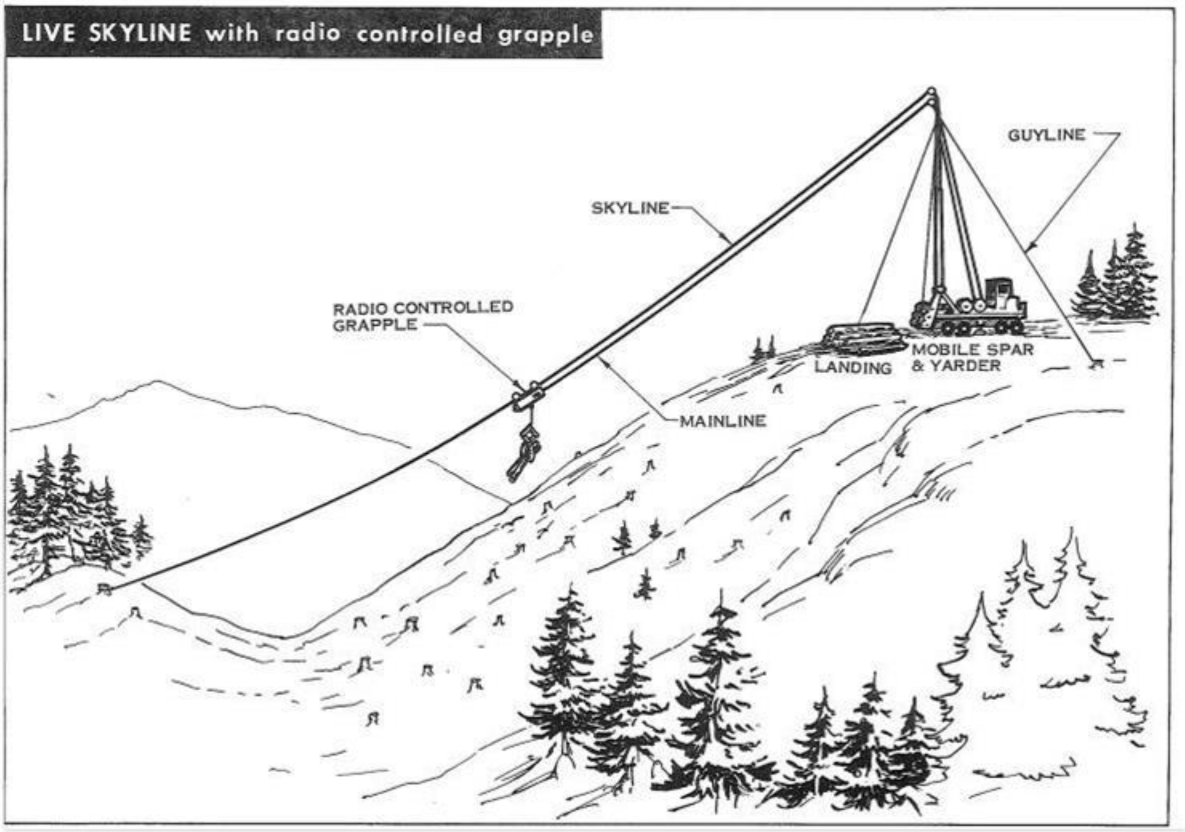


Figure 5.3: Live skyline with radio-controlled Falcon motorized grapple carriage in the shotgun configuration (Studier and Binkley 1974).

5.3.2 Data Collection

Shift level information was collected by researchers on site, including start and stop time, as well as all delays over 10 minutes. Relative crew information such as the number of crew members and their job title was recorded. The make, model and wire rope specifications of the yarder in use were obtained from the logging crew. In addition, the carriage type or butt rigging and their weight were also obtained from the crew. The position and elevation of the yarder and tail hold were recorded with a GPS unit. An additional GPS unit, which provided more detailed information on the carriage position during the cycle, was mounted to each carriage at study sites two through eight. The slope from yarder to tail hold, direction, and length were measured using an inclinometer, compass, and laser range finder, respectively.

Time study techniques were conducted to capture minor delays and to estimate the average delay-free cycle time based on the following observed elements:

Outhaul: Starts when the carriage moves away from the landing empty towards the cutover; and ends when the carriage stops along the skyline in preparation for the hook phase.

Hook: Begins when the carriage stops along the skyline after outhaul; and ends when the carriage grapples a stem or when stems are hooked by choker-setters, and begins to move along the skyline loaded, back towards the landing.

Inhaul: Begins when the carriage moves loaded towards the landing from the cutover; and ends when the carriage returns to the landing and pauses in preparation for the unhook phase.

Unhook: Begins when the carriage stops on return to the landing and drops the payload; and ends when the carriage moves away from the landing towards the cutover, marking the start of the outhaul phase.

In addition to the dependent variable of delay-free cycle time, independent variables and factors expected to influence the cycle elements were also recorded and defined as follows:

Span: The horizontal distance in meters, from the yarder tower to the tail hold.

Chord Slope: The slope of the skyline expressed in percent, from the yarder's skyline fairlead to where the skyline is connected to the tail hold.

Deflection: The amount of sag in the skyline, measured at mid-span and expressed as a percent of the total span length.

Configuration: The rigging configuration employed by the yarding crew; one of six choices (North Bend, North Bend Bridled, Acme Shotgun, Acme Slackline, Falcon Shotgun, Falcon Slackline).

Breakerouts: The number of breakerouts (choker setters) employed.

Chokers: The number of chokers attached to the rigging or carriage.

Chasers: Whether or not a chaser was employed; two choices (0=none/electronic chokers, 1= chaser unhooks chokers)

Distance: The yarding distance in meters measured from where the stems are hooked to the landing.

Pieces: The number of pieces yarded each cycle.

CyclVol: The total volume extracted per cycle in cubic meters, measured by the researcher at the landing.

PieceSize: The average volume of pieces yarded = *EstVol/Pieces.*

During the time study one researcher recorded the cycle elements by stop watch, while noting their associated factors and independent variables. The same researcher was also responsible for the setup of tension monitoring and video recording of operations. Video was captured by mounting a GoPro digital camera in the cutover on or near the anchor machine. The number of pieces per cycle and their type (stem, log, or top), their corresponding diameters (cm), length (m), and time of arrival were all recorded on the landing by another researcher. The same researcher was also responsible for the setup and collection of the carriage mounted GPS data.

5.3.3 Data Analysis

The recorded data were synchronized by clock time and then entered and analyzed in Microsoft Excel 2010[6], with statistical analysis performed in Minitab[7]. The data was screened for normality and outliers were removed before used to produce generalized linear models predicting delay-free cycle time. The cycle volumes measured were matched to their corresponding cycle by time of arrival to the landing, and used in conjunction with the cycle time to calculate productivity (m^3/PMH). Labor and energy consumption were calculated by dividing the total number of workers and total kW's of machinery by the productivity, respectively.

The yarding corridors and profiles were established by recording the position of the yarder and the corresponding tail hold using a GPS unit. The GPS points were then loaded into ArcMap 10.1[8] GIS software, in which the Skyline XL[9] program add-in tool was used to measure the distance and elevation along each corridor, to create a profile. The computer drawn profile was then exported to Skyline XL for payload analysis of a standing or live skyline system using the corresponding yarder and carriage combination, which were customized to match the specifications (i.e. tower height, kw, rope sizes, carriage weight, etc.) of the actual machines on site.

[6] Microsoft Excel Version 14.0.7109.500. Microsoft Corp., Redmond, Washington, USA

[7] Minitab Version 16.2. Minitab Inc., State College, PA, USA

[8] ArcMap Version 10.1. Environmental Systems Research Institute. Redlands, CA, USA

[9] SkylineXL Version 14.0, USDA Forest Service Research and Technology Development Center. San Dimas, CA, USA

5.4 Results & Discussion

This results section first presents a summary of the data collected at each of the eight sites. Subsequently, the data set is combined and analyzed with regard to productivity and then skyline tensions.

5.4.1 Study Site 1

Study site one was in Canterbury (Figure 5.4; Figure 5.5), was observed for two days across a total of three spans, in which 54 cycles were recorded. The Falcon Slackline rigging configuration was the only in use at this study site. The average cycle time (2.93 minutes) and volume (2.23 m^3) contributed to an average productivity rate of 46.5 (m^3/PMH) (Table 5.3). Corridors were located side by side, with relatively smooth terrain and were concave in shape. Payload analysis indicated that the limiting payload (1.9, 1.7 and 2.4 tons) was located at mid-span for profiles one through three, respectively (Figure 5.6). The yarder operator had a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during 21 of the cycles (39% frequency).

Figure 5.4: Falcon Slackline operation at study site one in Canterbury, viewed from the anchor position.

Table 5.3: Summary of the 54 observed cycle times and variables at study site one in Canterbury.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	**1**	0.87	258	0.87	1	1.3	0.82	0.10	0.00	2.65	29.2
2	**1**	0.52	253	0.98	1	2.2	0.87	0.05	0.00	2.42	53.9
3	**1**	0.53	249	2.73	2	1.1	1.50	0.13	0.00	4.90	13.2
4	**1**	0.63	251	1.65	1	0.4	1.13	0.17	0.00	3.58	6.9
5	**1**	0.67	266	0.87	2	2.5	1.03	0.12	0.48	2.68	55.5
6	**1**	0.48	265	1.03	1	1.3	0.87	0.12	0.53	2.50	30.5
7	**1**	0.72	262	0.97	2	0.3	1.17	0.17	0.00	3.02	5.6
8	**1**	0.75	259	1.00	2	1.9	0.98	0.15	0.00	2.88	40.0
9	**1**	0.45	110	0.58	1	0.5	1.27	0.17	1.92	2.46	11.9
10	**1**	0.75	257	0.93	3	0.9	1.23	0.10	0.00	3.02	18.5
11	**1**	0.63	257	0.87	2	1.8	1.48	0.13	0.00	3.12	35.0
12	**1**	0.68	275	0.78	1	3.3	1.02	0.10	0.00	2.58	75.9
13	**1**	0.72	257	1.75	4	2.5	1.72	0.17	0.00	4.35	34.1
14	**1**	0.73	267	2.52	2	5.0	0.85	0.17	0.00	4.27	70.3
15	**2**	0.55	130	0.72	1	1.5	0.57	0.10	0.00	1.93	46.6
16	**2**	0.28	127	0.80	1	1.9	0.45	0.12	0.00	1.65	69.8
17	**2**	0.30	150	1.32	1	3.5	0.65	0.23	0.00	2.50	83.8
18	**2**	0.27	118	2.38	2	4.3	1.50	0.10	1.05	4.25	61.3
19	**2**	0.45	153	1.17	2	1.7	0.68	0.12	0.00	2.42	42.5
20	**2**	0.43	94	0.63	1	2.2	0.37	0.15	0.00	1.58	82.2
21	**2**	0.43	157	1.05	1	0.6	0.75	0.10	0.00	2.33	16.2
22	**2**	0.32	149	0.62	1	2.4	0.85	0.08	1.37	1.87	76.0
23	**2**	0.43	158	1.43	2	3.1	0.57	0.18	0.00	2.62	72.0
24	**2**	0.25	170	2.83	1	3.2	1.65	0.10	1.70	4.83	39.8
25	**2**	0.40	159	1.57	1	3.3	0.72	0.25	0.18	2.93	68.1
26	**2**	0.38	174	2.07	1	0.2	0.95	0.22	0.00	3.62	4.0
27	**2**	0.42	183	1.70	1	0.2	0.72	0.13	0.00	2.97	4.0
28	**2**	0.62	180	0.95	1	3.7	1.60	0.27	0.00	3.43	64.8
29	**2**	0.50	189	0.82	1	3.5	0.72	0.10	0.00	2.13	97.6
30	**2**	0.35	195	0.90	1	2.2	0.92	0.15	0.00	2.32	56.2
31	**2**	0.55	214	0.88	1	2.2	0.83	0.12	0.00	2.38	54.6
32	**2**	0.42	245	1.03	1	0.8	0.93	0.10	0.00	2.48	18.6
33	**2**	0.42	233	1.10	1	2.2	1.27	0.15	1.32	2.93	44.4
34	**2**	0.57	224	0.55	1	2.2	0.98	0.20	0.00	2.30	56.6
35	**2**	0.53	238	1.15	2	4.3	1.87	0.18	0.00	3.73	69.8
36	**2**	0.62	244	0.70	1	2.2	1.72	0.17	1.17	3.20	40.7
37	**2**	0.47	247	1.00	1	0.4	0.87	0.12	0.00	2.45	10.5
38	**2**	0.42	243	1.63	1	0.4	0.87	0.12	0.00	3.03	8.5
39	**2**	0.60	200	1.23	2	2.6	1.85	0.12	0.12	3.80	41.1
40	**2**	0.87	236	1.92	2	2.9	1.35	0.18	0.00	4.32	40.9
41	**3**	0.57	216	0.63	1	1.5	0.90	0.13	0.00	2.23	39.0
42	**3**	0.48	204	0.72	1	1.6	0.75	0.12	0.00	2.07	46.2
43	**3**	0.55	219	0.63	2	0.6	0.70	0.07	0.57	1.95	18.2
44	**3**	0.40	235	1.13	1	2.1	1.17	0.12	0.00	2.82	45.4
45	**3**	0.62	239	1.00	2	2.9	0.85	0.12	0.00	2.58	68.3
46	**3**	0.60	236	0.80	2	2.8	1.37	0.12	0.00	2.88	58.1
47	**3**	0.50	225	0.73	1	1.9	1.23	0.20	1.57	2.67	41.9
48	**3**	0.55	247	1.45	2	5.6	2.00	0.13	0.00	4.13	81.7
49	**3**	0.65	258	1.35	1	3.4	1.35	0.15	0.00	3.50	59.0
50	**3**	0.92	260	0.82	1	3.4	1.18	0.15	1.42	3.07	65.5
51	**3**	0.65	272	1.07	1	2.6	1.17	0.12	0.00	3.00	52.6
52	**3**	0.48	268	1.63	1	5.8	1.45	0.13	2.65	3.70	93.7
53	**3**	0.68	263	0.77	2	1.7	0.87	0.10	0.00	2.42	43.0
54	**3**	0.57	273	1.08	1	2.1	0.97	0.13	0.00	2.75	45.2
Min		**0.25**	**94**	**0.55**	**1.0**	**0.20**	**0.37**	**0.05**	**0.00**	**1.58**	**4.0**
Max		**0.92**	**275**	**2.83**	**4.0**	**5.78**	**2.00**	**0.27**	**2.65**	**4.90**	**97.6**
Avg		**0.54**	**217**	**1.18**	**1.4**	**2.23**	**1.08**	**0.14**	**0.30**	**2.93**	**46.5**
SD		**0.15**	**49**	**0.55**	**0.6**	**1.33**	**0.38**	**0.04**	**0.62**	**0.78**	**24.5**

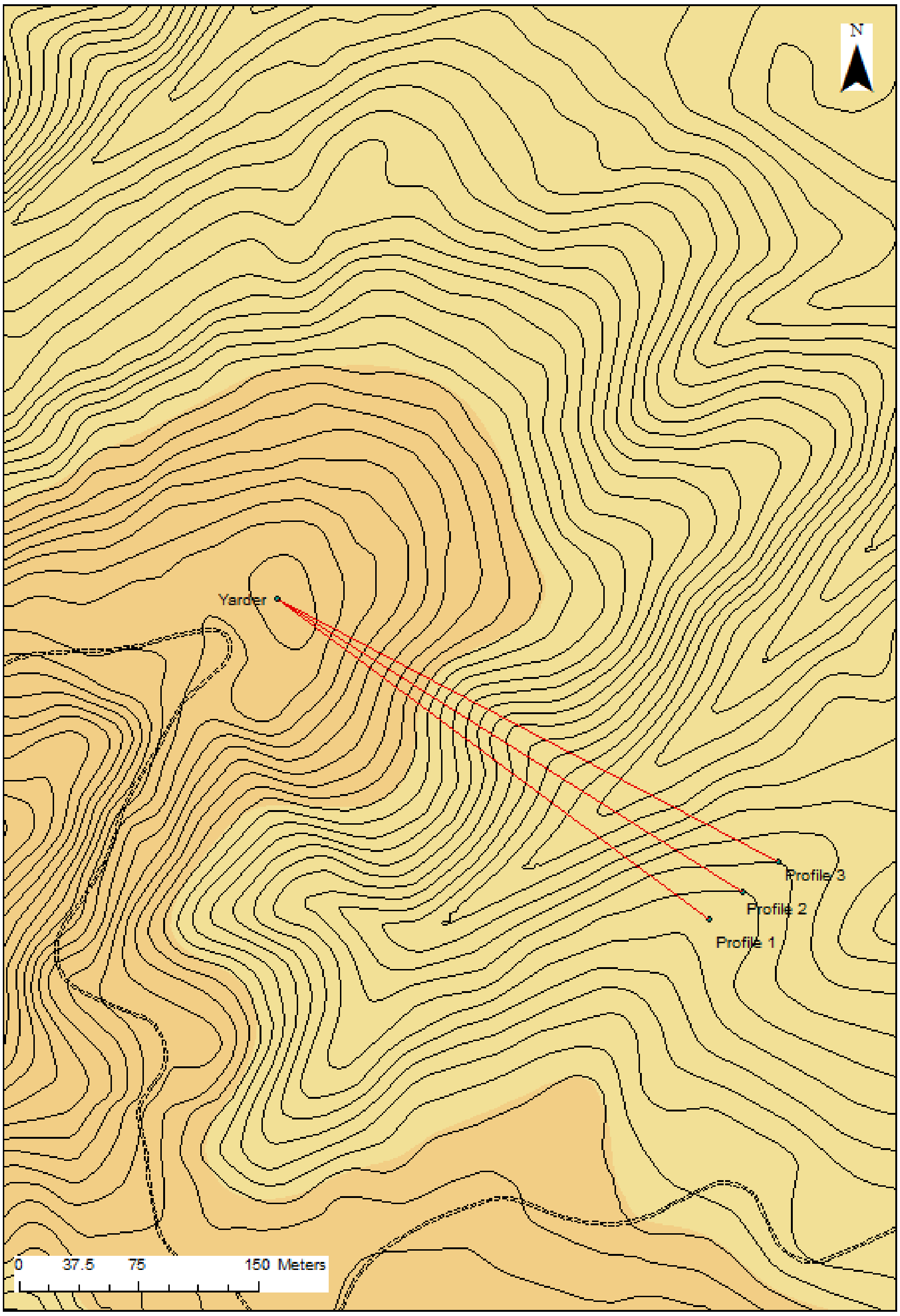


Figure 5.5: The ArcMap 10 meter contour elevation extracted profiles for payload analysis of each yarding corridor observed during the operation at study site one in Canterbury.

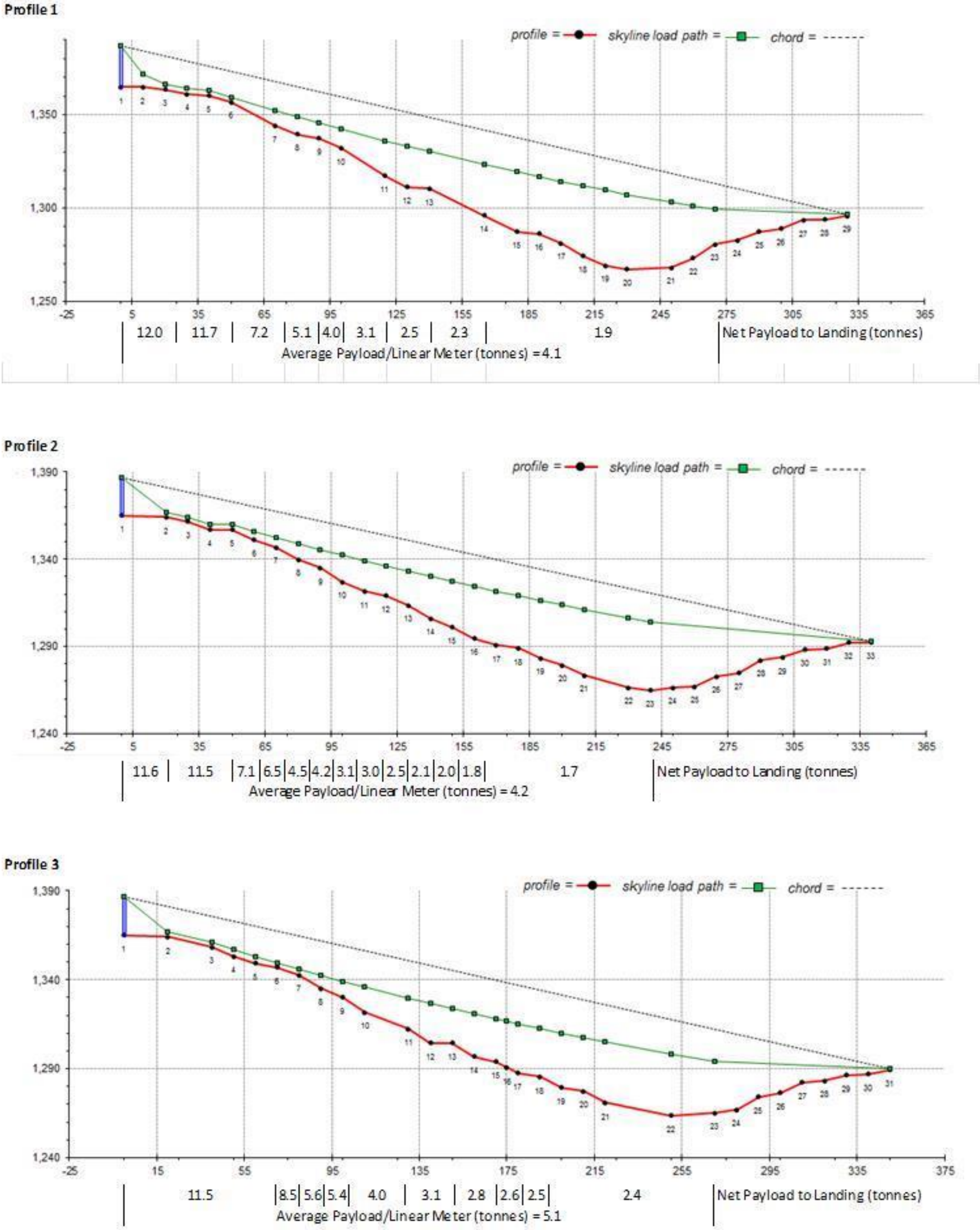


Figure 5.6: SkylineXL profile and payload analysis results for the Falcon Slackline operation at study site one in Canterbury.

Cycles one through 14 were recorded along the first profile, of which four cycles exceeded the safe working load (21.3 tons, 209 kN), either during inhaul or both hook and inhaul elements (Figure 5.7). The high tension behavior during the hook element, and carrying over into the inhaul element was due to how the configuration was operated. During each cycle, after the stems were grappled by the carriage, the skyline was tensioned to raise the carriage before inhaul, so that there was adequate clearance when the load approached the landing (Figure 5.6). The technique described facilitates fast inhaul speeds but at the sacrifice of increased skyline tension, even when transporting small loads. The maximum hook tension occurred during cycle nine, which transported a small load (0.5 tons) compared to cycle 14 which carried a large load (5.0 tons). The maximum inhaul tensions occurred during cycles 13 and 14 where payloads of 2.5 and 5.0 tons both exceeded the calculated limiting payload of 1.9 tons.

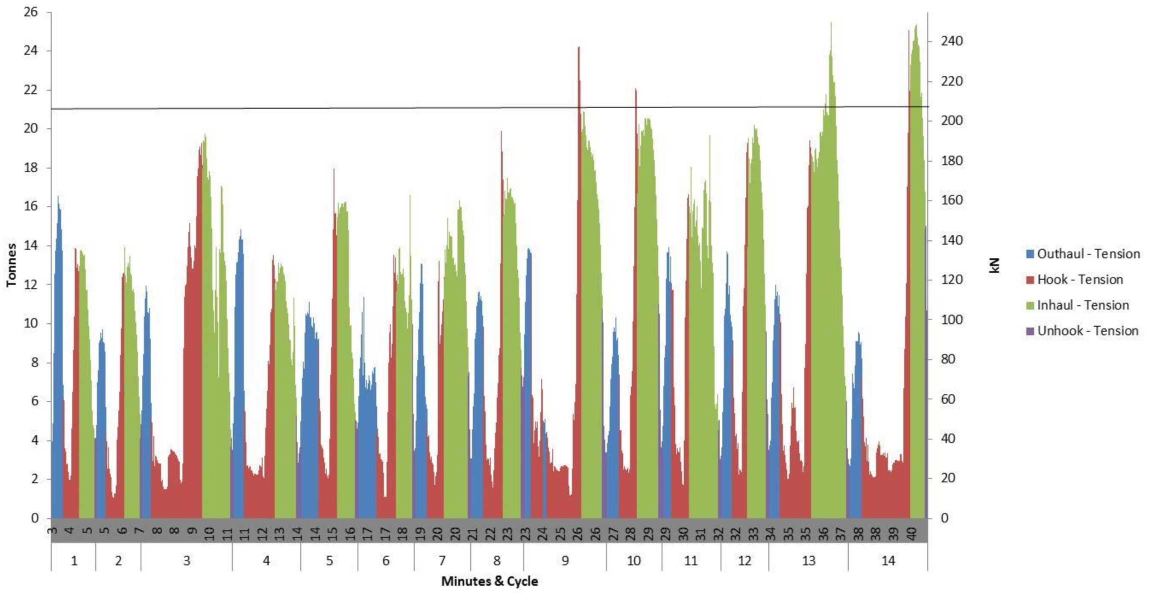


Figure 5.7: Skyline tensions for study site one, profile one, cycles 1-14, Falcon Slackline configuration.

Cycles 15 to 40 were recorded along the second profile which had less available deflection (5.9%), compared to the first profile, and therefore had higher maximum tensions which often exceeded the safe working load (Figure 5.7). The extraction distance for each cycle gradually increased as the carriage worked towards mid-span. However, the cycles extracted close to mid-span did not appear to generate higher skyline tensions, and there was considerable variation in tensions between cycles. The variation in tensions during hook and inhaul again highlight the variability in carriage height obtained through tensioning the skyline before inhaul.

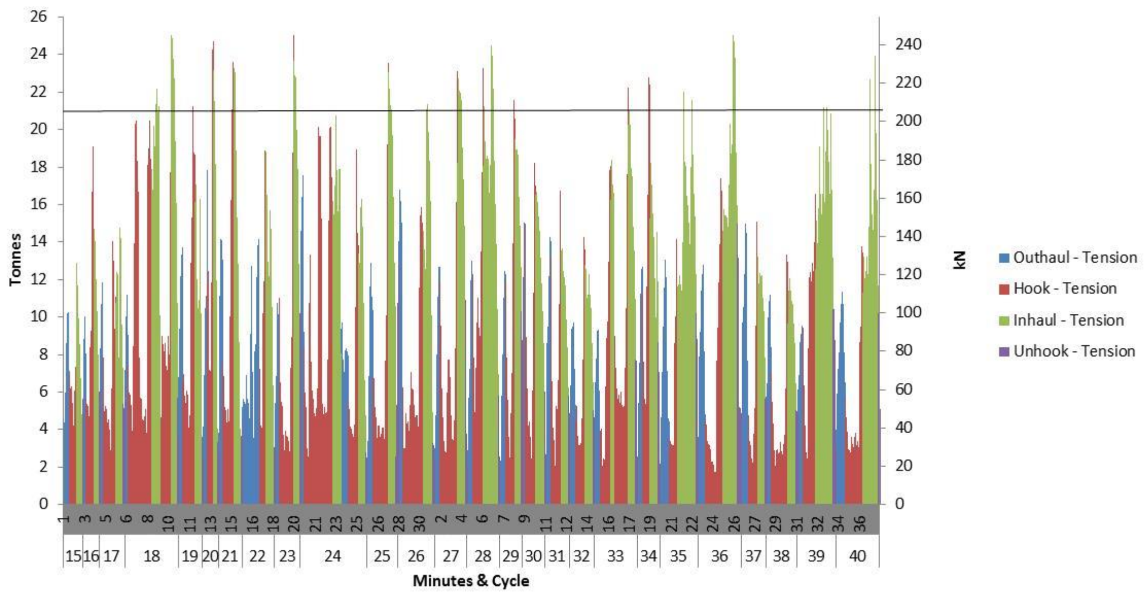


Figure 5.8: Skyline tensions for study site one, profile two, cycles 15-40, Falcon Slackline configuration.

Profile three was the last profile observed at this study site, where cycles 41-54 were recorded (Figure 5.9). The deflection was greater (7.4%) compared to the second profile as indicated by the lower maximum tensions recorded, where only four cycles exceeded the safe working load. It’s interesting to note the high peak tensions during outhaul with this configuration for all cycles observed (average 12.9 tons), compared to the low (approx. 4 tons) skyline pretension observed during the unhook element. The high outhaul peak tensions appear just as variable as the inhaul peak tensions, because the skyline is tensioned in the same way to raise the carriage for clearance near the landing, in addition to the empty carriage weight of over two tons.

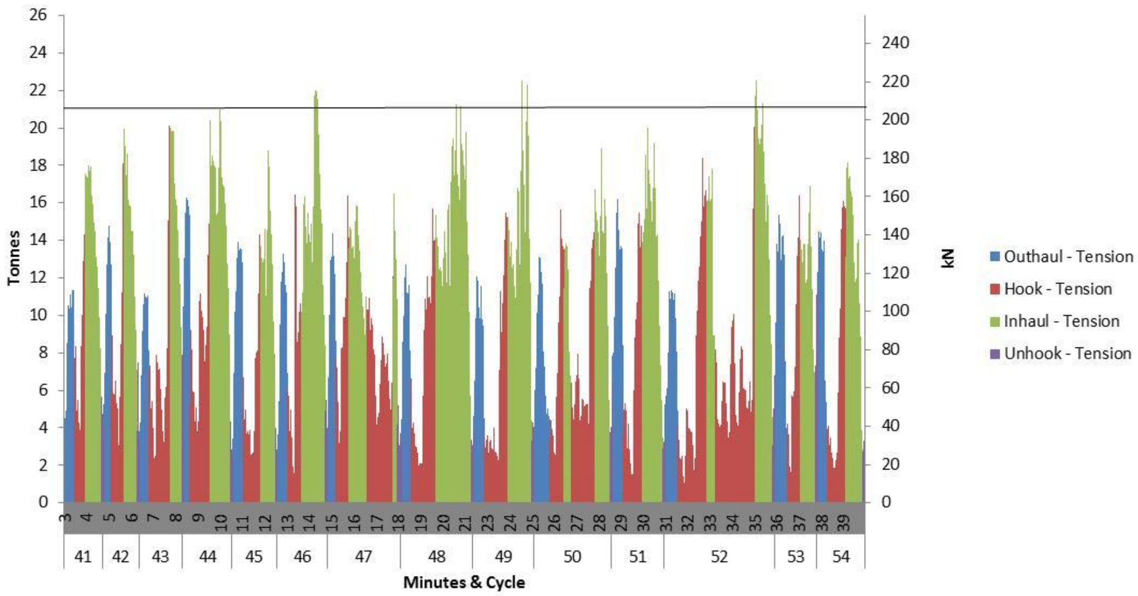


Figure 5.9: Skyline tensions for study site one, profile three, cycles 41-54, Falcon Slackline configuration.

5.4.2 Study Site 2

The operation at study site two in Nelson (Figure 5.10; Figure 5.11) was observed for one day across two spans, in which 31 cycles were recorded (Table 5.4). The adjacent corridors had relatively smooth terrain, were steep and straight to slightly concave in shape, and the anchor was placed on a slight ridge to provide deflection. The Falcon Shotgun rigging configuration was the only configuration in use at this study site. The average cycle time (2.20 minutes) and volume (2.09 m³) equates to an average productivity rate of 56.8 (m³/PMH). Payload analysis indicated that the limiting payload (7.2 and 7.3 tons) was located at mid-span for profiles one and two, respectively (Figure 5.12). The yarder operator had a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during 20 of the cycles (65% frequency).

Figure 5.10: Falcon Shotgun operation at study site two in Nelson, viewed from the anchor position.

Table 5.4: Summary of the 31 observed cycle times and variables at study site two in Nelson.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m³)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m³/PMH)
1	1	0.27	138	0.73	2	4.2	0.70	0.22	0.00	1.92	130.9
2	1	0.37	213	1.13	1	2.0	0.73	0.15	0.00	2.38	50.9
3	1	0.37	206	0.83	3	3.7	0.75	0.15	0.00	2.10	105.1
4	1	0.37	202	2.33	2	0.9	0.95	0.15	0.00	3.80	14.2
5	1	0.35	153	0.65	2	0.5	0.47	0.17	29.38	1.63	18.0
6	1	0.12	170	0.72	2	2.6	1.30	0.17	0.00	2.30	66.8
7	1	0.30	208	0.90	0	1.6	0.78	0.12	1.32	2.10	44.9
8	1	0.28	202	1.55	1	2.5	0.77	0.15	0.00	2.75	54.8
9	1	0.38	232	0.28	1	0.8	0.70	0.12	0.00	1.48	31.1
10	1	0.35	208	0.48	1	1.4	0.67	0.13	0.00	1.63	50.0
11	1	0.43	269	0.72	2	1.2	0.73	0.15	0.00	2.03	35.1
12	1	0.35	242	1.07	2	3.1	0.75	0.22	0.00	2.38	79.0
13	1	0.30	263	1.08	2	1.4	0.62	0.12	0.00	2.12	40.5
14	1	0.35	213	0.50	1	0.9	0.67	0.18	0.00	1.70	30.7
15	1	0.40	272	1.07	2	1.6	0.85	0.15	0.00	2.47	39.9
16	1	0.25	273	0.87	2	3.8	1.05	0.17	0.00	2.33	97.7
17	1	0.37	291	1.03	2	4.0	0.98	0.10	3.90	2.48	97.6
18	2	0.38	223	0.57	1	1.3	1.00	0.13	0.00	2.08	38.0
19	2	0.35	218	0.80	1	1.9	0.97	0.17	0.00	2.28	50.2
20	2	0.37	242	0.57	1	1.9	0.80	0.18	0.00	1.92	60.7
21	2	0.37	234	0.38	2	0.9	0.77	0.18	0.00	1.70	31.1
22	2	0.37	224	0.43	2	1.7	1.00	0.18	0.00	1.98	51.1
23	2	0.32	220	0.35	2	3.7	1.07	0.17	0.13	1.90	115.6
24	2	0.42	252	0.90	1	3.7	0.63	0.15	0.00	2.10	104.6
25	2	0.37	250	0.78	1	1.4	0.97	0.17	0.00	2.28	37.8
26	2	0.38	225	0.75	2	3.4	1.03	0.15	0.00	2.32	88.6
27	2	0.42	257	0.55	1	0.6	0.80	0.20	0.00	1.97	19.2
28	2	0.35	205	1.55	2	3.4	0.97	0.25	0.00	3.12	65.5
29	2	0.42	210	0.48	1	0.3	0.95	0.17	4.73	2.02	7.7
30	2	0.40	193	0.90	1	1.2	0.58	0.18	2.38	2.07	35.4
31	2	0.33	253	1.48	1	3.2	0.92	0.10	0.00	2.83	67.6
Min		**0.12**	**138**	**0.28**	**0.0**	**0.26**	**0.47**	**0.10**	**0.00**	**1.48**	**7.7**
Max		**0.43**	**291**	**2.33**	**3.0**	**4.18**	**1.30**	**0.25**	**29.38**	**3.80**	**130.9**
Avg		**0.35**	**225**	**0.85**	**1.5**	**2.09**	**0.84**	**0.16**	**1.35**	**2.20**	**56.8**
SD		**0.06**	**35**	**0.43**	**0.6**	**1.20**	**0.18**	**0.03**	**5.33**	**0.47**	**31.8**

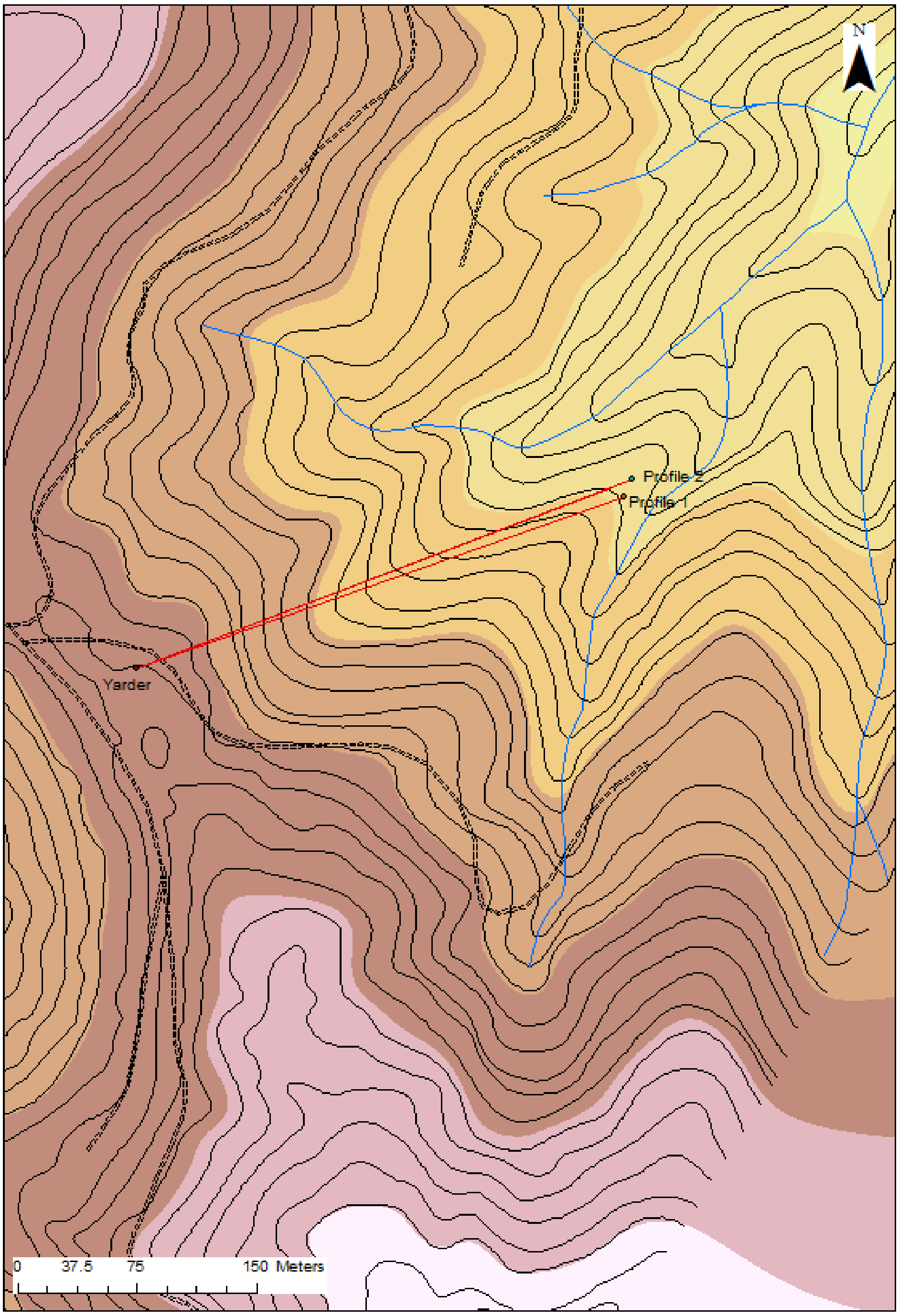
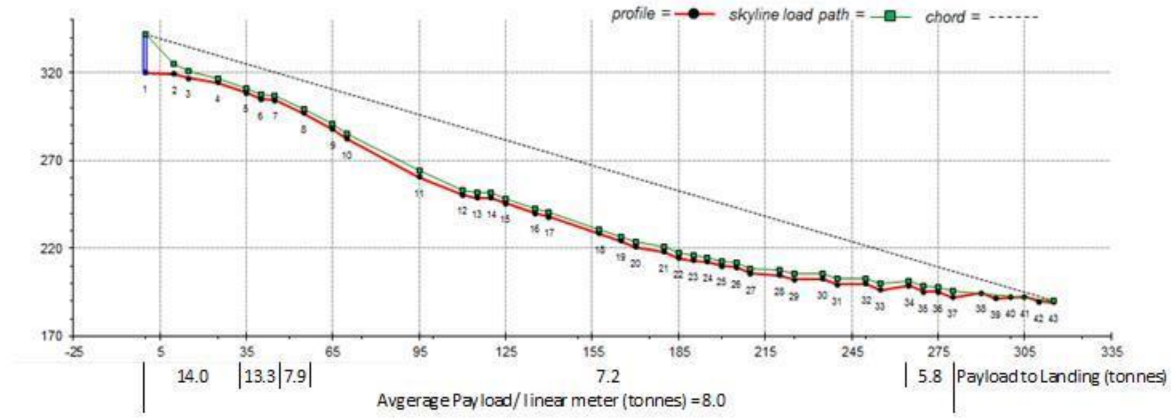


Figure 5.11: The ArcMap 10 meter contour elevation extracted profiles for payload analysis of each yarding corridor observed during the operation at study site two in Nelson.

Profile 1



Profile 2

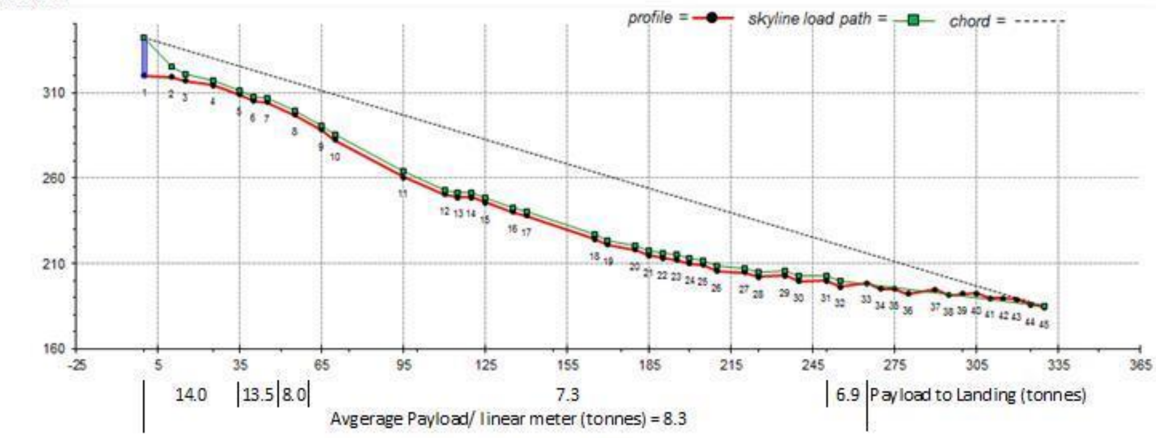


Figure 5.12: SkylineXL profile and payload analysis results for the Falcon Shotgun operation at study site two in Nelson.

Cycles one through 16 were recorded along profile one, of which 10 cycles exceeded the safe working load (21.3 tons, 209 kN), (Figure 5.13). Skyline tensions exhibited similar behavior to the Falcon Slackline configuration at study site one, with high tensions observed during the hook and inhaul elements of the cycle. However, the configuration was operated differently than study site one; where the skyline was tensioned to lift the carriage and logs to only what was adequate to start inhaul. Once inhaul commenced one or more skyline “lifts” (i.e. further tensioning of the skyline) was performed to achieve clearance over terrain before arriving at the landing. In other words, the operator was trying to mirror the ground slope with the carriage during inhaul in an attempt to maximize deflection, most likely due to the poor available deflection of (5.7%). The steep chord slope (-47 %) allowed fast outhaul of the carriage (0.3 to 0.4 minutes) compared to study site one even with similar distances. There were some issues with stems slipping out of the carriage grapple during inhaul, as evident in cycle seven, where the stem was re-grappled before inhaul continued. Maximum tensions during outhaul were high (average 17 tons) compared to the skyline pretension (approx. 4 tons); and the highest (21.2 tons) was recorded during cycle 16. This high tension, probably together with the high frequency vibration, knocked the tension monitor off the skyline when the carriage came within 25 meters of the anchor machine.

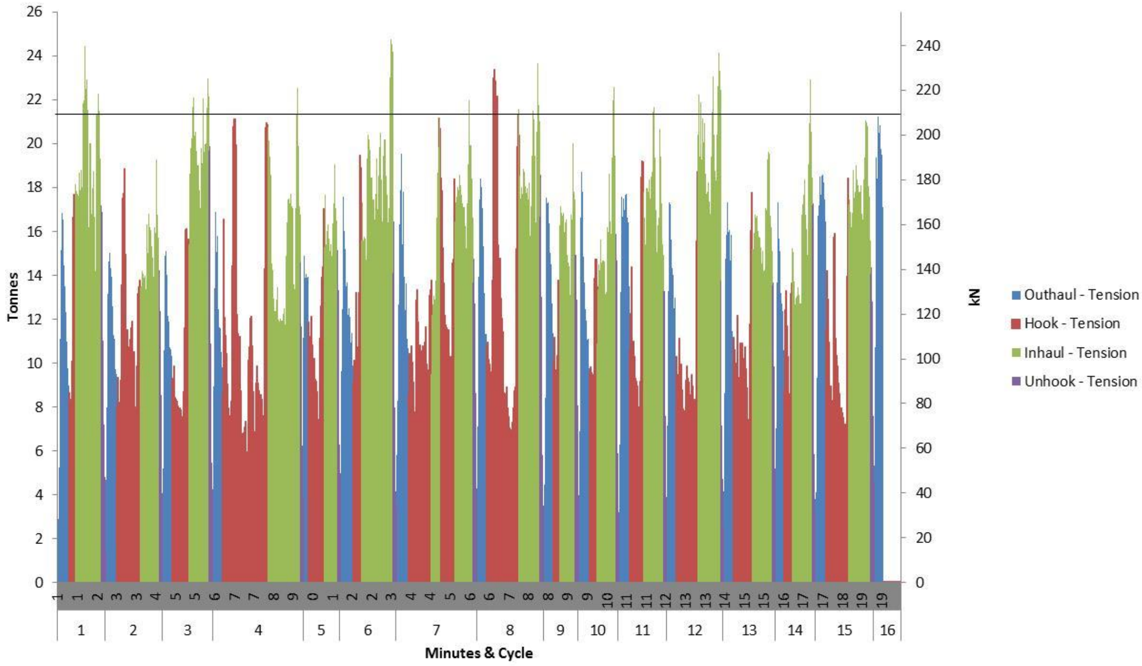


Figure 5.13: Skyline tensions for study site two, profile one, cycles 1-16, Falcon Shotgun configuration.

A skyline shift allowed the tension monitor to be reconnected to the skyline and tension monitoring resumed for cycles 18 to 31 which were all recorded across the second profile (Figure 5.14). Delays recoded during cycle 29 & 30 were due to checking the carriage hydraulic oil and refueling the carriage. Similar problems existed with stems slipping out of the grapple and having to be re-grappled as evident in cycle 29. It is also interesting to note, in comparison to study site one, the high cyclic loading which occurred during inhaul in both profile one and two. The cyclic loading indicated by the peak to peak differences in tension are a result of the different operating procedures; where the stems had more ground contact during inhaul at study site two.

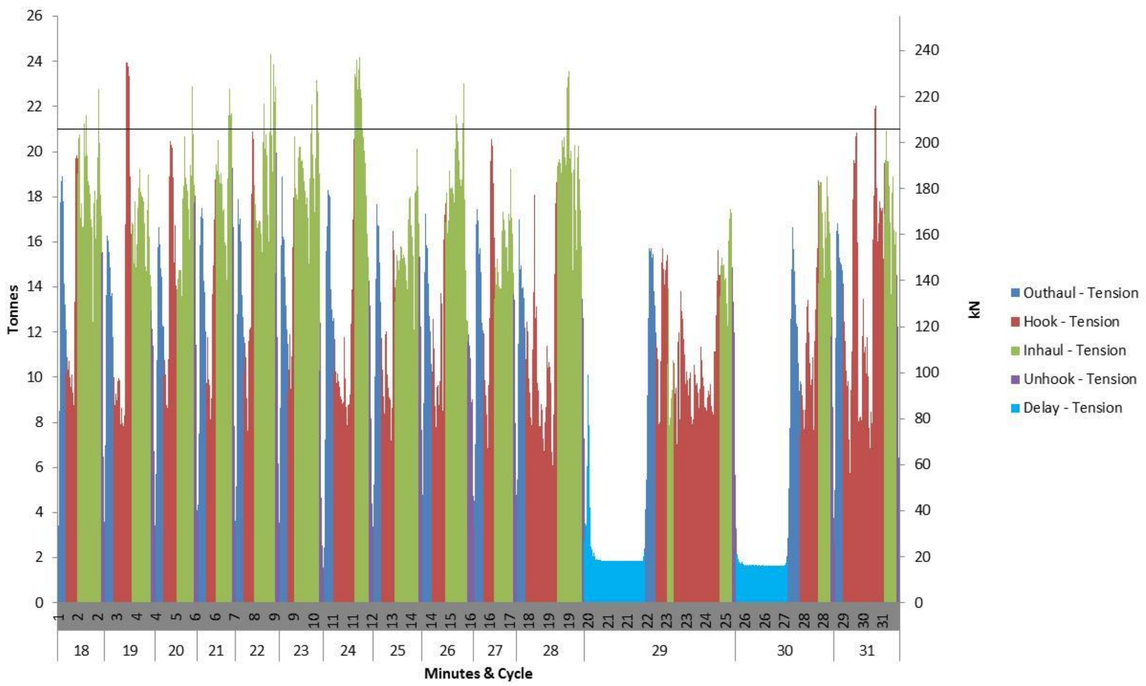


Figure 5.14: Skyline tensions for study site two, profile two, cycles 18-31, Falcon Shotgun configuration.

5.4.3 Study Site 3

The operation at study site three in Gisborne (Figure 5.15; Figure 5.16) was observed for two days across two long spans (>900 m), in which 19 cycles were recorded (Table 5.5). Significant delays in the operation on both days did not provide the opportunity to collect the desired minimum 30 cycles. The corridors were located next to one another with steep and broken terrain, but the anchor was situated on the other side of the valley to provide deflection. North Bend was the primary configuration used at this site. However, topography in an area located close to the yarder but off-set laterally (>100 m) did not provide an adequate anchor location. In order to reach stems in this difficult area without being able to move the skyline required the use of the North Bend Bridled configuration (cycles 15-19). With an average cycle time (9.60 minutes) and volume (6.5 m^3) average productivity rate was 45.5 (m^3/PMH). Payload analysis indicated that the limiting payload for profile one (1.4 tons) was located at mid-span, while the limiting payload for profile two (3.9 tons) was located at the extent of yarding distance (Figure 5.17). The yarder operator did not have a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during 14 of the cycles (75% frequency).

Figure 5.15: North Bend & North Bend Bridled operation at study site three in Gisborne, viewed from the anchor position.

Table 5.5: Summary of the 19 observed cycle times and variables at study site three in Gisborne.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	**1**	1.48	245	5.93	4	6.5	1.42	1.83	0.00	10.67	36.5
2	**1**	0.52	250	2.33	3	7.0	1.23	0.58	0.00	4.67	90.3
3	**1**	1.23	240	3.43	3	6.0	1.12	0.87	0.00	6.65	53.8
4	**1**	1.02	250	2.57	4	9.3	1.67	0.82	0.00	6.07	91.7
5	**1**	1.58	285	3.75	3	8.7	2.18	1.13	0.00	8.65	60.3
6	**1**	1.93	285	3.70	3	8.3	2.72	0.87	0.00	9.22	54.2
7	**1**	1.20	260	3.77	3	5.0	1.43	3.85	0.00	10.25	29.4
8	**1**	1.28	260	5.72	4	6.9	2.35	3.15	0.00	12.50	33.1
9	**1**	0.57	290	5.03	4	7.8	1.57	1.60	0.00	8.77	53.3
10	**1**	4.17	300	3.93	3	6.2	2.70	0.57	0.00	11.37	32.9
11	**1**	1.13	310	1.58	2	6.5	3.00	0.75	10.17	6.47	60.7
12	**1**	1.75	310	3.48	2	4.2	2.40	0.87	0.00	8.50	29.5
13	**1**	1.28	310	12.47	2	6.9	2.07	2.43	0.00	18.25	22.7
14	**1**	2.45	320	6.10	2	4.8	5.93	0.25	9.58	14.73	19.6
15	**2**	1.33	100	3.43	1	3.6	1.03	0.48	2.90	6.28	34.8
16	**2**	1.12	100	5.80	2	5.8	1.17	1.43	46.65	9.52	36.6
17	**2**	4.38	120	4.80	3	8.7	1.58	1.08	0.00	11.85	44.1
18	**2**	1.13	140	3.10	2	5.8	1.78	0.88	0.00	6.90	50.4
19	**2**	1.42	160	6.52	2	5.8	2.35	0.80	0.00	11.08	31.4
Min		**0.52**	**100**	**1.58**	**1.0**	**3.6**	**1.03**	**0.25**	**0.00**	**4.67**	**19.6**
Max		**4.38**	**320**	**12.47**	**4.0**	**9.3**	**5.93**	**3.85**	**46.65**	**18.25**	**91.7**
Avg		**1.63**	**239**	**4.60**	**2.7**	**6.5**	**2.09**	**1.28**	**3.65**	**9.60**	**45.5**
SD		**1.03**	**75**	**2.35**	**0.9**	**1.6**	**1.10**	**0.94**	**10.87**	**3.32**	**20.2**

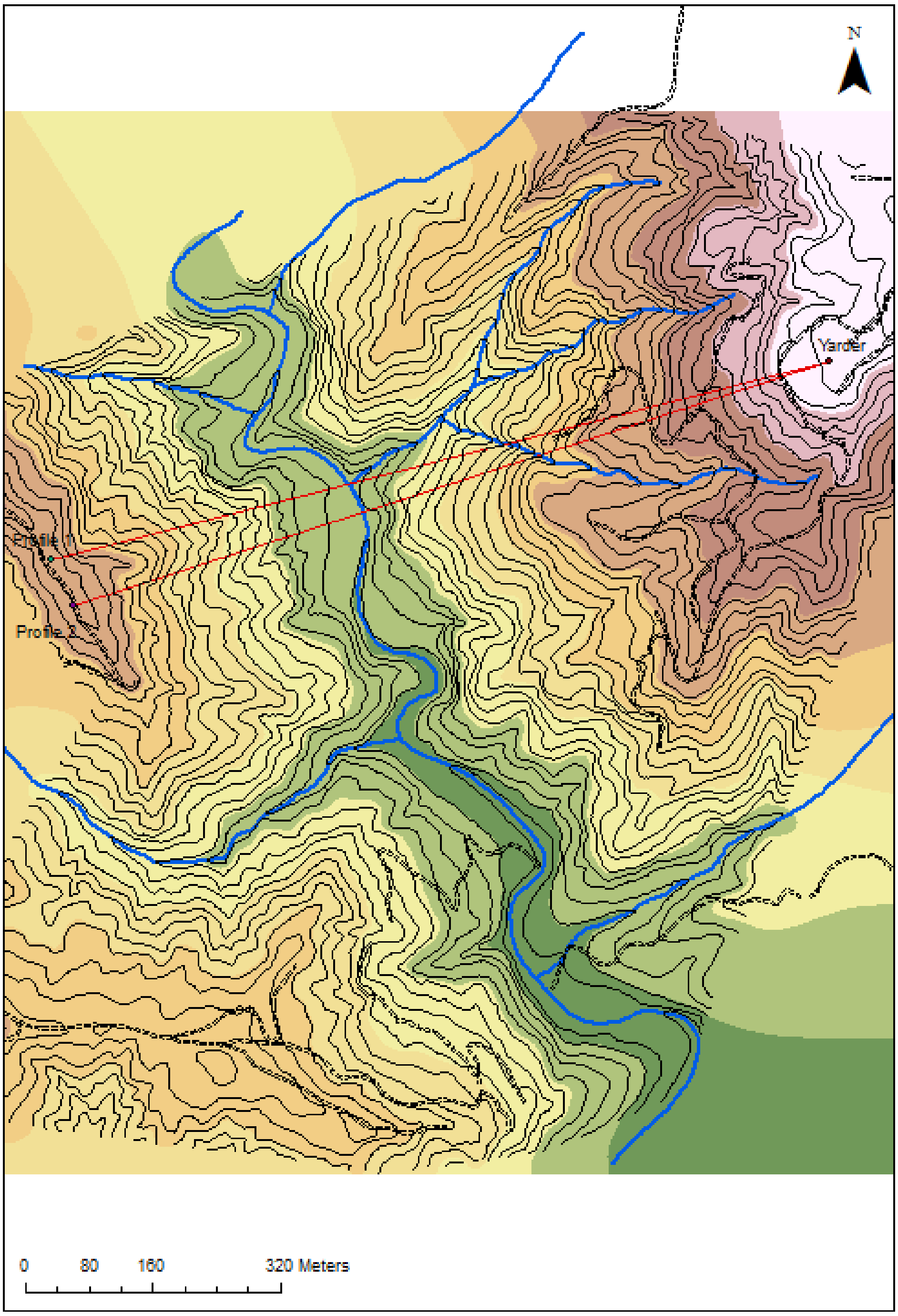
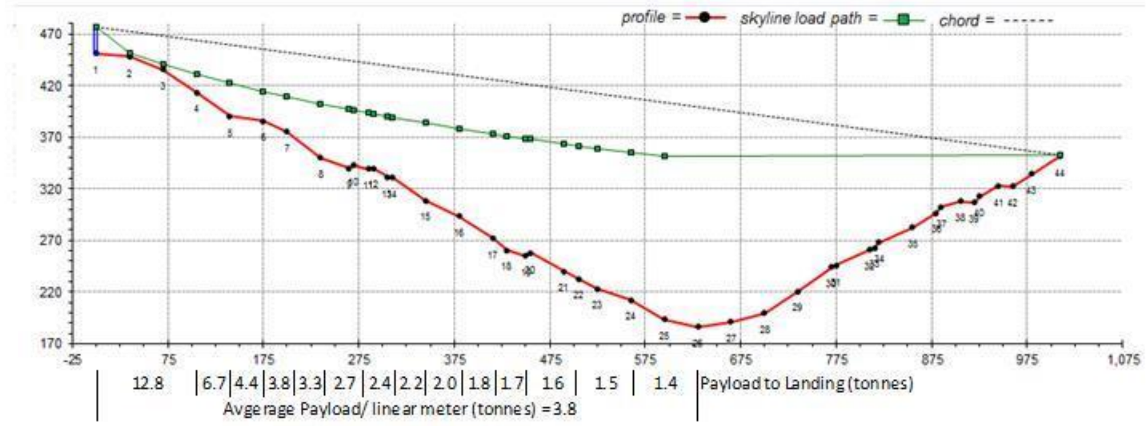


Figure 5.16: The ArcMap 10 meter contour elevation extracted profiles for payload analysis of each yarding corridor observed during the operation at study site three in Gisborne.

Profile 1



Profile 2

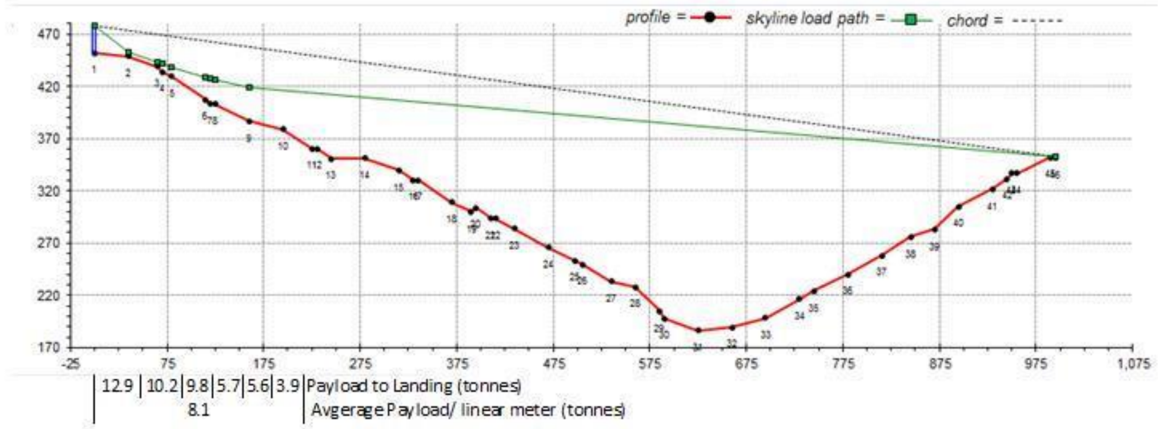


Figure 5.17: SkylineXL profile and payload analysis results for the North Bend and North Bend Bridled operation at study site three in Gisborne.

Cycles one through nine were recorded on the first day of the operation and were all from profile one utilizing the North Bend configuration (Figure 5.18). Skyline tensions in this setup were relatively high in all elements of the cycle, and each of the nine cycles exceeded the safe working load of 21.3 tons (209 kN). The high pretention in the skyline (13-14 tons) was apparent by the minimum tension occurring during the unhook element. The high pretension was likely a function of the weight of the skyline and operating cables having to be suspended across the >900 meter span length, with the low associated deflection (5.2%).

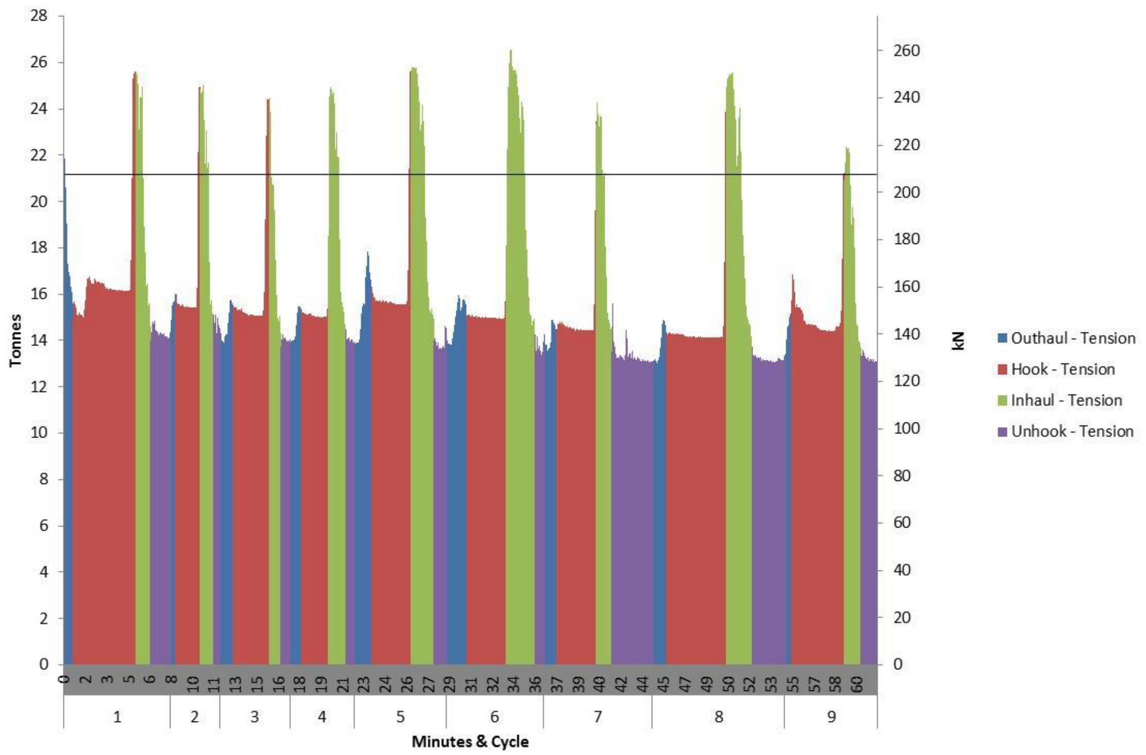


Figure 5.18: Skyline tensions for study site three, profile one, cycles 1-9, North Bend configuration.

Yarding resumed across the first span the following day with cycles 10-14 (Figure 5.19). Peak tensions during inhaul exceeded the safe working load on four out of the five cycles. Low deflection and a blind lead area caused hang-ups during inhaul, where stems had to be unhooked; as indicated by the several minutes of delay in cycle 11 & 14. The hang-up in cycle 14 caused the mainline to disconnect form the carriage; a skyline shift to profile two occurred during the down time.

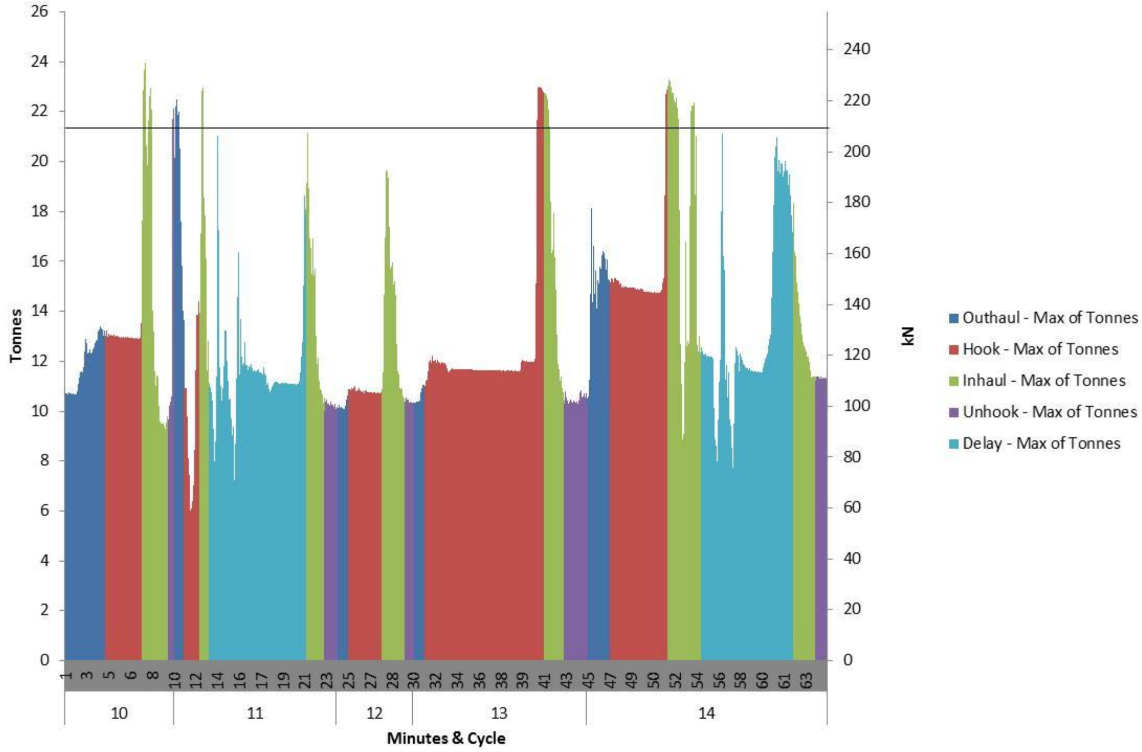


Figure 5.19: Skyline tensions for study site three, profile one, cycles 10-14, North Bend configuration.

After the skyline shift to profile two occurred, the configuration was changed to North Bend Bridled. The haulback blocks were placed just below the road due south of the yarder in Figure 5.16. Cycle 15 was the first of the North Bend Bridled configuration and although extraction was from a different location, a hang-up occurred during inhaul (Figure 5.20).

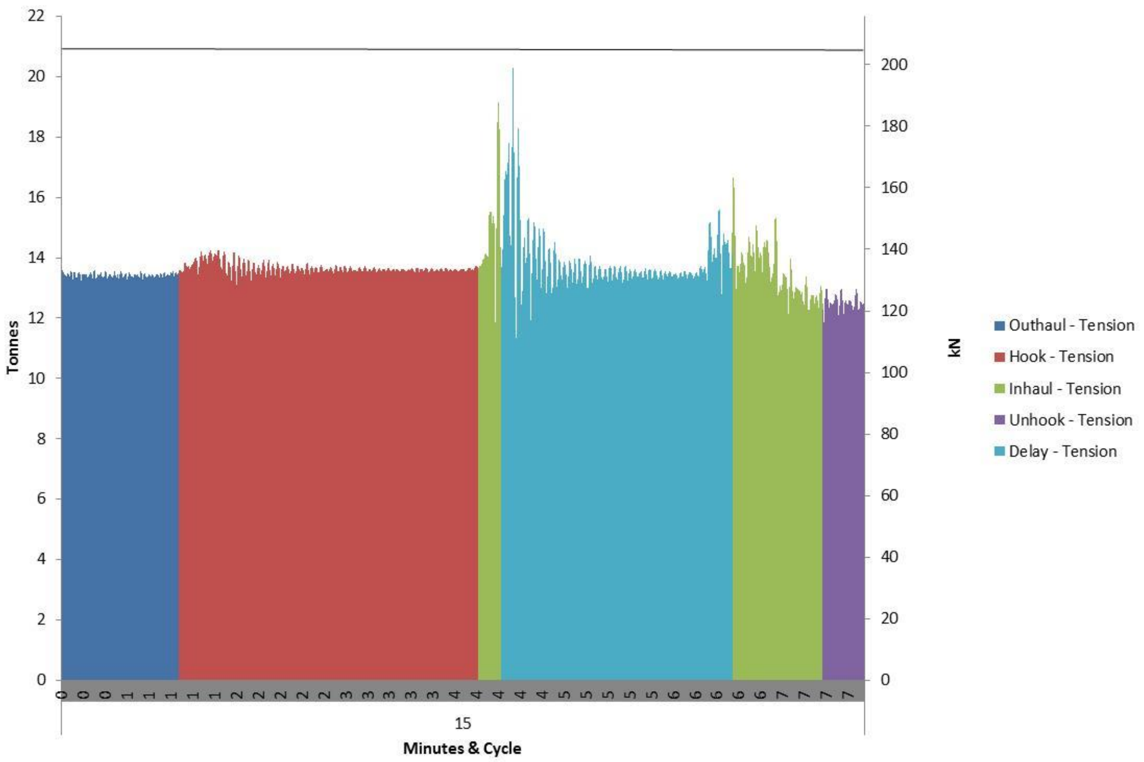


Figure 5.20: Skyline tensions for study site three, profile two, cycle 15, North Bend Bridled configuration.

The haulback block was moved again after cycle 15 to avoid the hang-up issue, and yarding resumed with cycles 16 through 19 (Figure 5.21). Cycle 16 was the only one of all the North Bend Bridled cycles to exceed the safe working load. Note the effect of off-setting the haulback blocks during the Bridled cycles on tension behavior. There was little difference in tensions between the outhaul, hook and unhook elements as compared to cycles 1-14; somewhat of a damping effect.

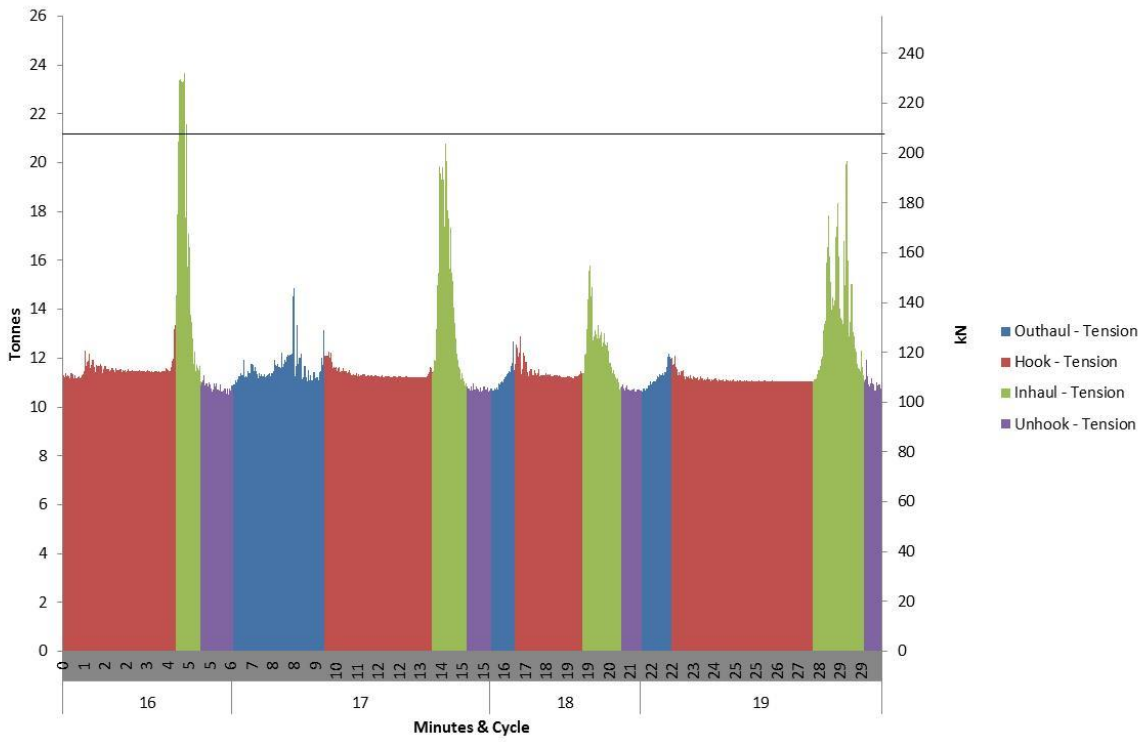


Figure 5.21: Skyline tensions for study site three, profile two, cycles 16-19, North Bend Bridled configuration.

5.4.4 Study Site 4

The operation at study site four in Gisborne (Figure 5.22; Figure 5.23), was observed for one day across two spans, in which 22 cycles were recorded (Table 5.6). The corridors were located next to one another with relatively smooth, but steep terrain that was concave in shape. Acme Slackline was the only configuration used at this study site, and was what the crew was most experienced with. The average cycle time (7.44 minutes) and volume (6.0 m^3) meant that the configuration had an average productivity rate of 48.8 (m^3/PMH). Payload analysis indicated that the limiting payload (2.0 and 3.7 tons) was located at mid-span for profiles one and two, respectively (Figure 5.24). The yarder operator did not have a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during 21 of the cycles (95% frequency).

Figure 5.22: Acme Slackline operation at study site four in Gisborne, viewed from the anchor position.

Table 5.6: Summary of the 22 observed cycle times and variables at study site four in Gisborne.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	1	0.43	154	5.52	3	6.6	0.87	0.68	1.02	7.50	52.8
2	1	0.13	160	3.98	2	7.5	0.80	0.25	0.00	5.16	87.2
3	1	0.32	165	6.23	2	3.8	1.50	0.18	3.63	8.23	27.7
4	1	0.47	186	7.40	2	4.0	0.95	0.22	0.00	9.03	26.6
5	1	0.33	191	4.97	3	7.5	1.52	1.20	0.00	8.02	56.1
6	1	0.45	191	8.55	3	8.6	1.22	1.02	0.92	11.23	45.9
7	1	0.52	213	6.57	3	9.1	2.58	0.15	2.65	9.81	55.6
8	2	0.53	208	7.27	3	7.1	0.97	1.00	0.00	9.77	43.6
9	2	0.27	221	4.47	2	9.1	1.37	0.68	0.00	6.78	80.5
10	2	0.55	248	4.50	3	6.6	1.80	1.88	0.00	8.73	45.3
11	2	0.43	246	5.80	2	6.7	1.97	0.60	0.00	8.80	45.7
12	2	0.70	260	4.57	3	5.6	0.65	0.98	0.52	6.90	48.7
13	2	0.62	263	2.67	3	7.0	2.10	0.30	0.27	5.68	73.9
14	2	0.57	265	3.85	3	8.0	2.58	0.57	0.00	7.57	63.4
15	2	1.02	307	2.07	2	4.4	3.35	0.20	0.68	6.63	39.8
16	2	0.90	313	3.48	2	4.7	3.50	0.32	0.00	8.20	34.4
17	2	0.92	315	1.73	1	3.6	1.97	0.22	0.00	4.83	44.7
18	2	1.28	318	3.27	11	5.0	1.95	0.62	0.15	7.12	42.2
19	2	0.62	317	2.95	3	4.3	2.60	0.28	0.00	6.45	40.0
20	2	0.67	317	1.93	2	4.0	3.00	0.10	2.58	5.70	42.1
21	2	1.62	317	1.20	2	5.1	2.82	0.80	0.00	6.43	47.6
22	2	0.65	317	1.83	1	2.6	1.78	0.87	0.00	5.13	30.4
Min		**0.13**	**154**	**1.20**	**1.0**	**2.6**	**0.65**	**0.10**	**0.00**	**4.83**	**26.6**
Max		**1.62**	**318**	**8.55**	**11.0**	**9.1**	**3.50**	**1.88**	**3.63**	**11.23**	**87.2**
Avg		**0.64**	**250**	**4.31**	**2.8**	**6.0**	**1.90**	**0.60**	**0.56**	**7.44**	**48.8**
SD		**0.34**	**59**	**2.06**	**2.0**	**1.9**	**0.84**	**0.44**	**1.04**	**1.69**	**15.8**

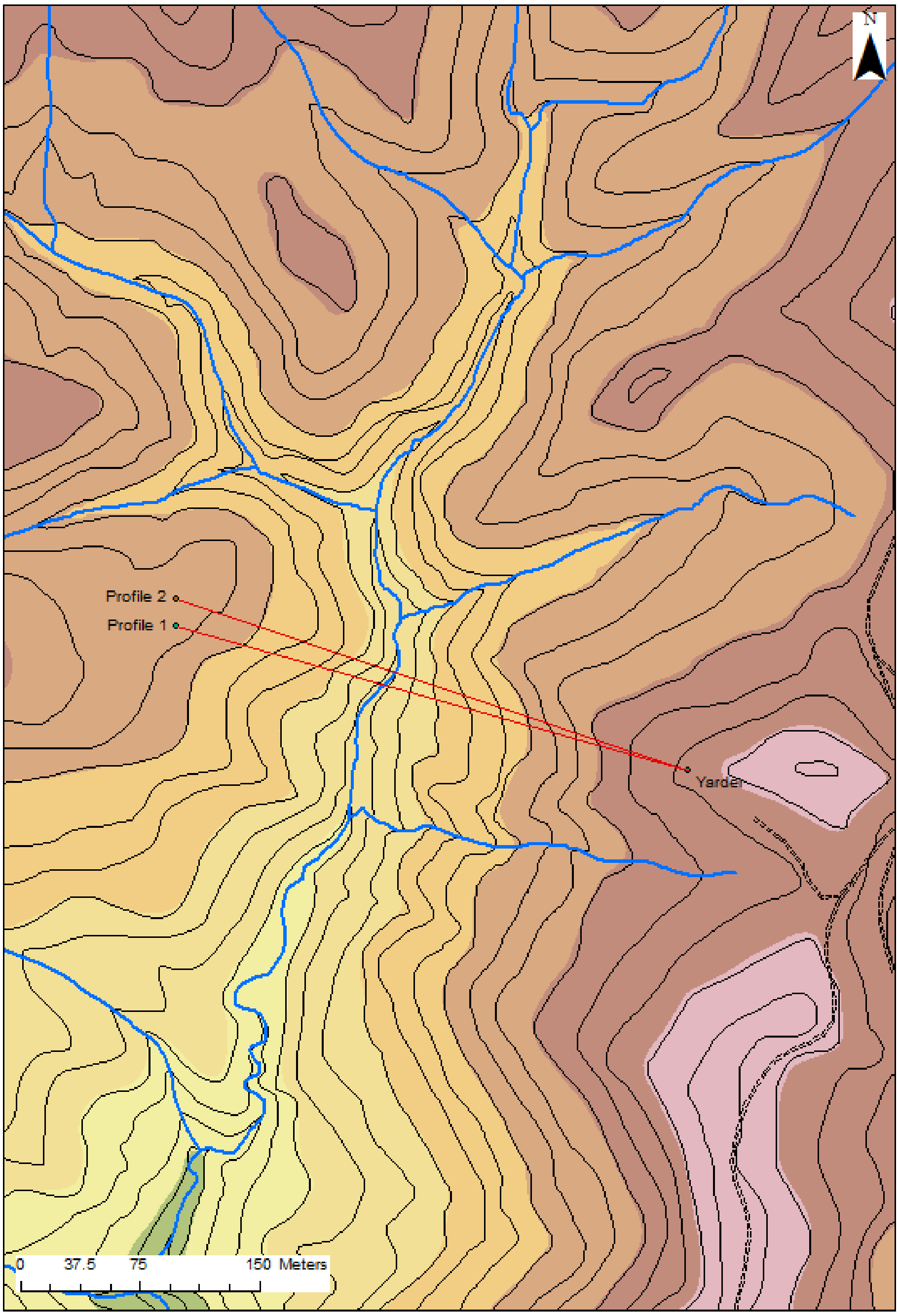
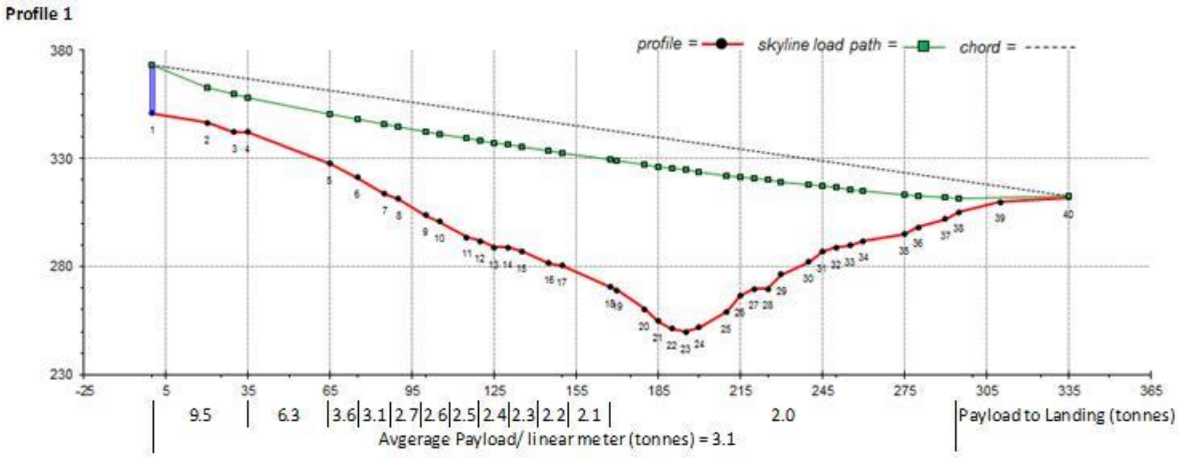


Figure 5.23: The ArcMap 10 meter contour elevation extracted profiles for payload analysis of each yarding corridor observed during the operation at study site four in Gisborne.



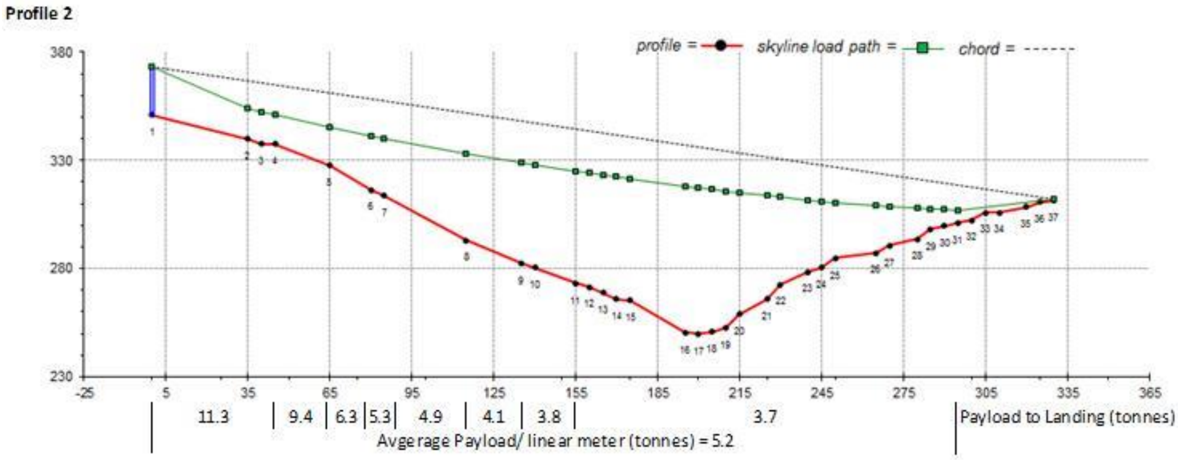


Figure 5.24: SkylineXL profile and payload analysis results for the Acme Slackline operation at study site four in Gisborne.

Cycles one through seven were recorded across profile one, whereby every cycle exceeded the safe working load of 21.3 tons (209 kN), often by over 30% (Figure 5.25; Figure 5.26). It’s interesting to note the effect of the carriage skyline clamp on tension behavior, indicated by the peaks at the beginning and end of the hook element. The delays associated with cycle one were due to the loader having to clear the chute before stems could be landed, followed by having to re-land the stems so they rest properly on the landing before unhooking; similar delays occurred on cycles six and seven. The longer delay at the start of cycle three was due to a change of chokers on the carriage. Cycle seven also had a hang-up during inhaul and one stem had to be unhooked before inhaul could resume.

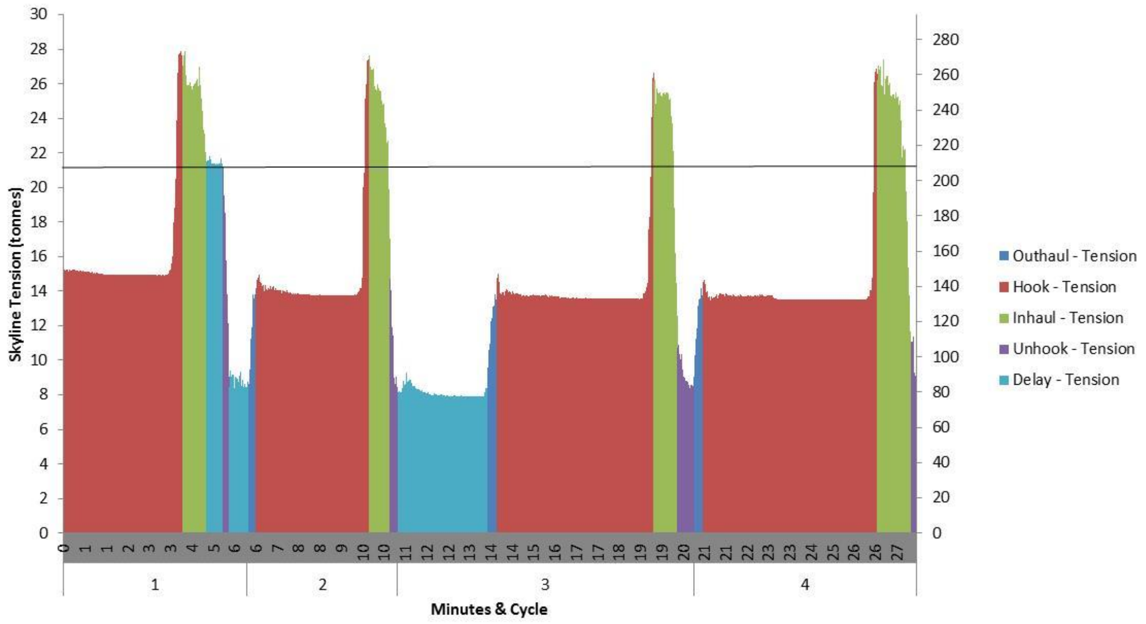


Figure 5.25: Skyline tensions for study site four, profile one, cycles 1-4, Acme Slackline configuration.

Cycles 8 to 14 were recorded across profile two where deflection had increased from 4.2 to 6.1% but, each cycle continued to exceed the safe working load (Figure 5.26). Interaction delays with the loader clearing the chute and having to re-land logs for stability issues persisted in cycles 10, 12 and 13.

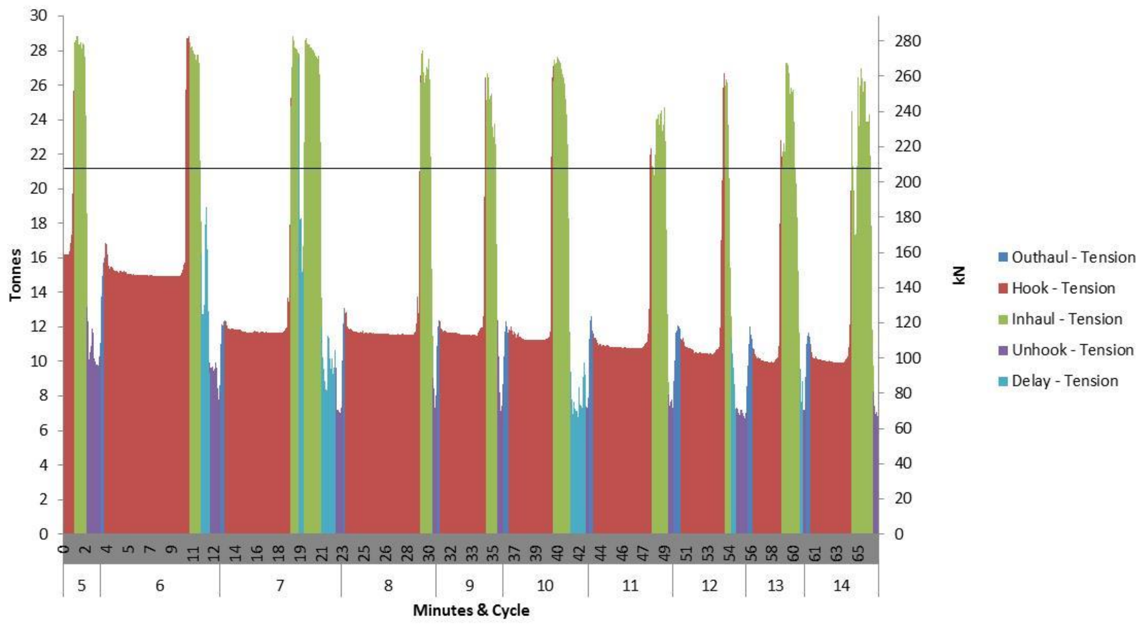


Figure 5.26: Skyline tensions for study site four, profile one, cycles 5-7 and Profile two, cycles 8-14, Acme Slackline configuration.

The final cycles (15-22) recorded along profile two were different in tension behavior than the previous cycles (Figure 5.27). The stems were extracted from the back face of the canyon, out of a stock pile of stems just in front of the anchor machine. Note the peaks in the outhaul tension as the carriage crossed mid-span and the comparative reduction in hook tensions, since the carriage was not resting near mid-span during the hook element for cycles 15 to 22. One interesting behavior noticed in the final recorded cycles, was the high cyclic loading compared to earlier cycles; which was due to a change in inhaul strategy. The operator was trying to drag the stems along the ground during inhaul from the back face, even though full suspension was achievable. There was a noticeable reduction in cyclic loads when the load was fully suspended during cycle 17; there was also a reduction in peak inhaul tension and inhaul element time. Compared to other configurations at other study sites, the peak tensions observed in this operation were relatively consistent but also high as most exceeded 26 tons (256 kN), which could be associated with the carriage skyline clamp.

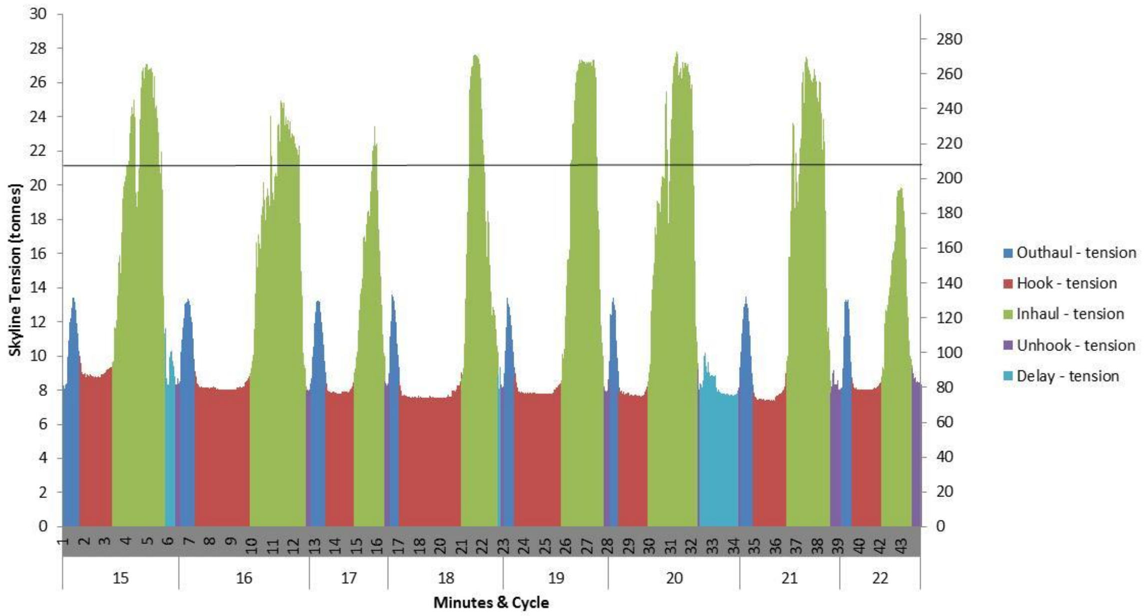


Figure 5.27: Skyline tensions for study site four, profile two, cycles 15-22, Acme Slackline configuration.

5.4.5 Study Site 5

The operation at study site five in Nelson (Figure 5.28; Figure 5.29), was observed for one day across one long span (>600 m) in which 34 cycles were recorded (Table 5.7). However, the maximum yarding distance was just over 250 m. The corridor had smooth terrain with a straight shape, which meant that the anchor had to be elevated on the other side of the valley to provide deflection. Falcon Shotgun was the only configuration in use at this study site. An average cycle time (2.84 minutes) and volume (2.20 m³) contributed to an average productivity rate of 47.7 (m³/PMH). Payload analysis indicated that the limiting payload (5.1 tons) was located at the extent of the yarding distance for profile one (Figure 5.30). The yarder operator had a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during 15 of the cycles (44% frequency).

Figure 5.28: Falcon Shotgun operation at study site five in Nelson, viewed from the anchor position.

Table 5.7: Summary of the 34 observed cycle times and variables at study site five in Nelson.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m³)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m³/PMH)
1	**1**	0.45	123	0.72	1	1.4	0.65	0.37	0.65	2.19	39.0
2	**1**	0.82	118	1.18	2	2.3	0.83	0.20	0.00	3.03	45.4
3	**1**	0.43	127	1.37	1	0.3	0.43	0.33	0.00	2.57	6.6
4	**1**	0.50	132	0.90	2	4.4	0.57	0.28	0.00	2.25	117.1
5	**1**	0.58	137	0.93	1	1.4	0.73	0.57	0.00	2.82	29.8
6	**1**	0.43	141	1.38	2	3.9	1.00	0.57	0.00	3.38	69.1
7	**1**	0.58	154	0.63	1	2.1	0.73	0.75	0.67	2.70	47.6
8	**1**	0.38	160	0.62	1	3.1	0.72	0.32	0.00	2.03	91.8
9	**1**	0.45	166	1.02	2	2.7	1.67	0.30	0.75	3.43	47.3
10	**1**	0.35	173	0.55	1	2.1	0.52	0.53	0.00	1.95	64.4
11	**1**	0.37	171	0.73	2	3.3	0.92	0.48	0.00	2.50	78.2
12	**1**	0.37	178	0.43	1	1.5	0.77	0.52	0.00	2.08	44.0
13	**1**	0.43	177	0.73	2	3.5	1.07	0.63	0.00	2.87	72.6
14	**1**	0.40	186	0.37	2	2.5	1.45	0.35	4.42	2.57	58.4
15	**1**	0.40	186	0.42	2	1.7	1.10	0.48	0.00	2.40	43.1
16	**1**	0.53	194	0.73	2	3.2	1.15	0.30	0.38	2.72	69.7
17	**1**	0.52	198	0.30	3	1.9	1.17	0.53	0.00	2.52	44.4
18	**1**	0.42	205	0.97	1	1.2	0.90	0.50	0.47	2.78	25.7
19	**1**	0.72	204	0.53	1	1.0	1.08	0.52	0.00	2.85	22.0
20	**1**	0.52	207	1.18	1	3.5	1.20	0.22	0.30	3.12	67.5
21	**1**	0.90	217	0.48	1	2.1	1.47	0.50	1.27	3.35	37.4
22	**1**	0.52	222	1.15	1	2.9	1.57	0.50	0.77	3.73	47.3
23	**1**	0.43	209	1.05	1	0.8	1.73	0.23	2.55	3.45	13.4
24	**1**	0.42	222	0.68	1	3.7	1.38	0.43	0.00	2.92	76.6
25	**1**	0.50	220	0.98	1	1.3	1.20	0.63	0.00	3.32	23.3
26	**1**	0.40	219	1.35	1	0.2	1.63	0.22	0.60	3.60	3.7
27	**1**	0.55	226	0.42	1	4.7	1.55	0.52	0.00	3.03	92.0
28	**1**	0.50	235	0.53	1	2.8	1.43	0.47	0.00	2.93	57.9
29	**1**	0.37	252	0.73	1	2.8	1.72	0.78	0.00	3.60	47.2
30	**1**	0.25	130	1.28	1	1.8	0.67	0.57	0.00	2.77	38.2
31	**1**	0.27	144	1.13	1	0.7	0.80	0.45	0.00	2.65	15.2
32	**1**	0.42	152	0.42	2	0.8	0.68	0.32	0.00	1.83	24.7
33	**1**	0.45	245	1.25	1	1.6	1.42	0.45	0.57	3.57	26.1
34	**1**	0.77	239	0.85	1	1.8	1.35	0.20	0.85	3.17	35.0
Min		**0.25**	**118**	**0.30**	**1.0**	**0.2**	**0.43**	**0.20**	**0.00**	**1.83**	**3.7**
Max		**0.90**	**252**	**1.38**	**3.0**	**4.7**	**1.73**	**0.78**	**4.42**	**3.73**	**117.1**
Avg		**0.48**	**184**	**0.82**	**1.4**	**2.2**	**1.10**	**0.44**	**0.42**	**2.84**	**47.7**
SD		**0.14**	**39**	**0.33**	**0.5**	**1.2**	**0.38**	**0.15**	**0.88**	**0.51**	**26.0**

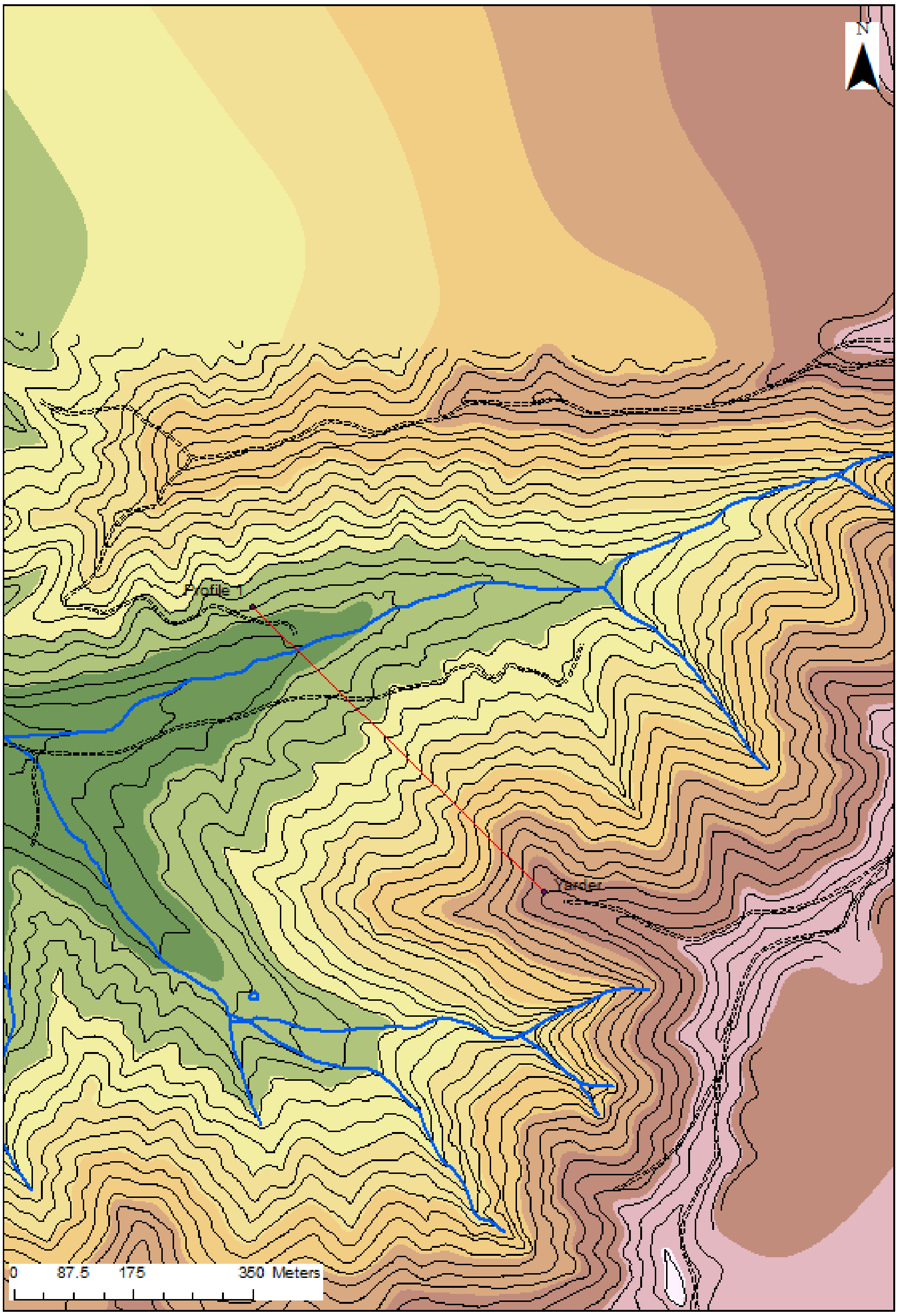


Figure 5.29: The ArcMap 10 meter contour elevation extracted profile for payload analysis of the yarding corridor observed during the operation at study site five in Nelson.

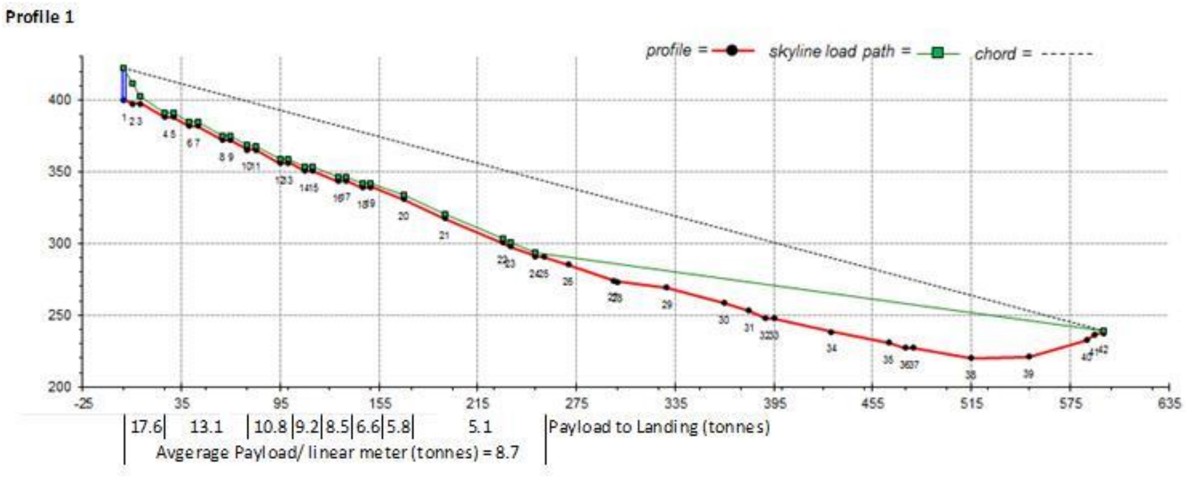


Figure 5.30: SkylineXL profile and payload analysis results for the Falcon Shotgun operation at study site five in Nelson.

Cycles one through 17 were recorded along profile one, where seven of the 17 cycles exceeded the safe working load of 21.3 tons (209 kN), (Figure 5.31). Similar skyline tension behavior exists as observed at study site one and two, as a live skyline system was used and the carriage mirrored the ground slope during inhaul. However, the longer span at this study site (>600 m) and the relatively low deflection (6.1%) resulted in very similar peak tensions of the outhaul, hook and inhaul elements. The quick average cycle times (2.8 min) made it difficult for the loader operator to keep the landing clear, as indicated by the interaction delay (i.e. waiting for loader) in cycles one, 14 and 16.

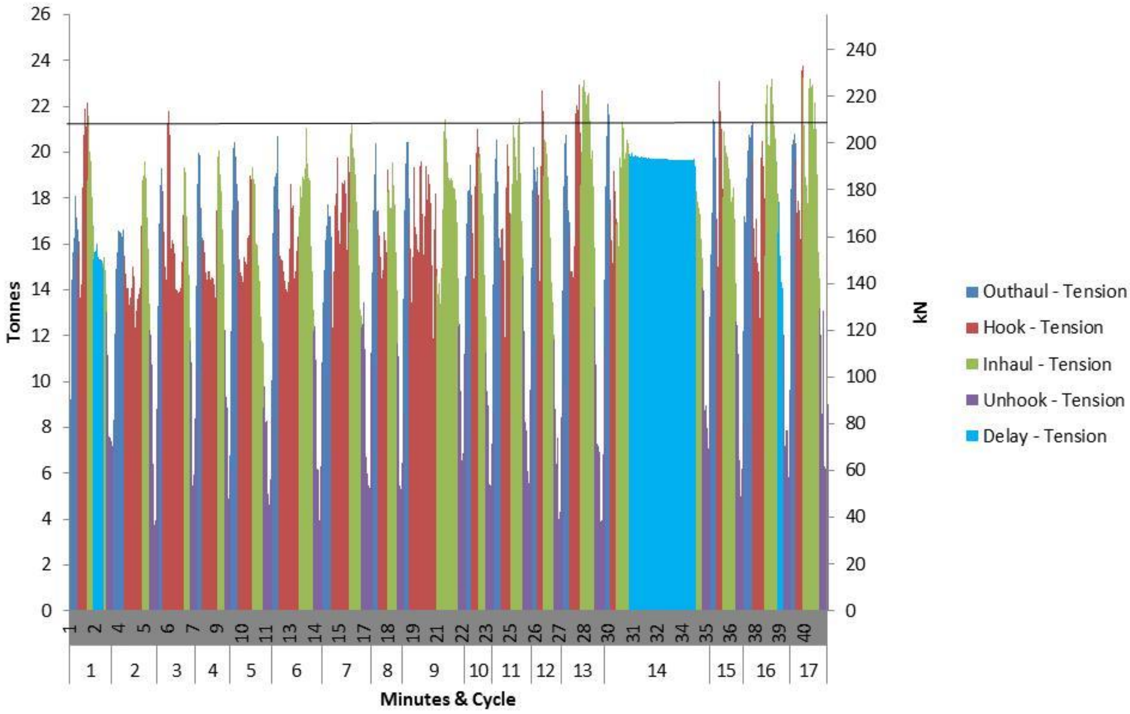


Figure 5.31: Skyline tensions for study site five, profile one, cycles 1-17, Falcon Shotgun configuration.

Cycles 18 to 34 were also recorded along profile one, of which six cycles exceeded the safe working load (Figure 5.32). Extraction distance continued to increase with each cycle towards mid-span but there was no apparent increase in peak tensions. Many delays occurred during these cycles like the loader interaction (cycle 16 & 20), having to wait for a worker to move from under the skyline (cycle 22), and having to re-grapple stems broken or lost during inhaul (cycle 18, 23, 26 and 33). Compared to the other Falcon configurations studied, this study site had the highest peak tensions, which was likely due to the span, deflection, and carriage weight as previously discussed.

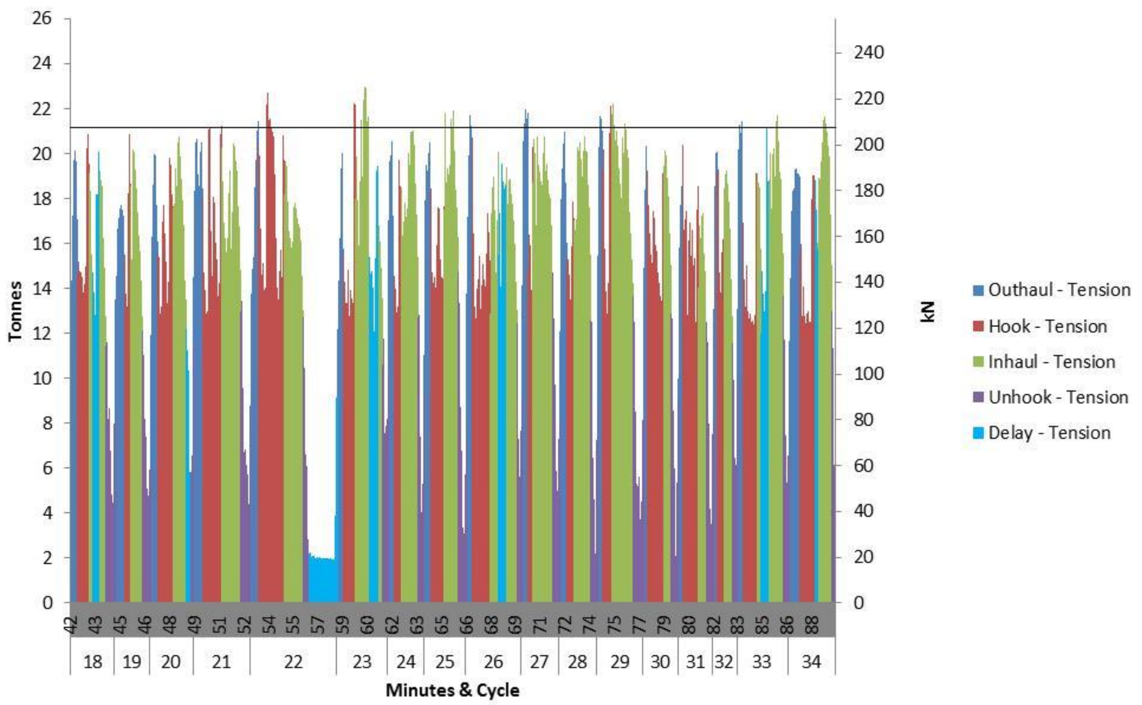


Figure 5.32: Skyline tensions for study site five, profile one, cycles 18-34, Falcon Shotgun configuration.

5.4.6 Study Site 6

The operation a study site six in Marlborough (Figure 5.33; Figure 5.34), was observed for two days across one long span (1,100 m) in which 34 cycles were recorded (Table 5.8). However, the maximum yarding distance observed was 475 m. The corridor had very steep and broken terrain that had a straight shape, so the anchor had to be extended across the valley bottom to provide deflection. North Bend Bridled was the only configuration in use at this study site and provided the means to yard trees laterally away from the native bush boundary and power lines. With an average cycle time (9.26 minutes) and volume (4.7 m^3) the configuration had an average productivity rate of 32.2 (m^3/PMH). Payload analysis indicated that the limiting payload (0.0 tons) was located at approximately 300 m from the yarder, where a blind lead resulted in insufficient carriage clearance (Figure 5.35). The yarder operator did not have a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during 22 of the cycles (65% frequency).

Figure 5.33: North Bend Bridled operation at study site six in Marlborough, viewed from the anchor position.

Table 5.8: Summary of the 34 observed cycle times and variables at study site six in Marlborough.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	**1**	1.00	218	3.93	2	7.4	1.73	1.42	0.00	8.08	54.9
2	**1**	1.17	229	2.83	2	4.2	1.25	0.87	0.00	6.12	40.7
3	**1**	0.72	221	3.58	1	0.5	1.17	0.67	0.00	6.13	4.4
4	**1**	0.75	240	2.95	1	3.2	1.32	0.67	0.00	5.68	33.8
5	**1**	0.98	245	2.95	2	9.0	1.72	0.80	0.00	6.45	83.7
6	**1**	1.07	250	3.13	2	7.7	1.40	1.07	0.00	6.67	69.3
7	**1**	1.42	258	4.28	3	7.5	1.65	1.55	0.00	8.90	50.6
8	**1**	1.00	264	3.88	1	2.6	1.27	0.32	0.00	6.47	24.1
9	**1**	0.80	248	3.85	2	9.4	1.63	0.58	6.00	6.87	82.1
10	**1**	1.23	261	3.92	4	6.2	1.47	1.02	0.00	7.63	48.7
11	**1**	1.07	258	4.82	2	4.5	1.65	1.78	2.27	9.32	29.0
12	**1**	0.93	260	4.02	2	4.5	1.45	0.78	0.00	7.18	37.6
13	**1**	1.22	255	2.88	3	5.8	3.25	0.95	1.27	8.30	41.9
14	**1**	0.95	260	3.62	2	6.0	1.75	1.77	1.68	8.08	44.5
15	**1**	1.40	280	3.63	2	6.5	2.03	1.27	33.00	8.33	46.8
16	**1**	1.08	270	5.60	2	7.6	1.82	2.05	0.00	10.55	43.2
17	**1**	1.00	270	5.55	2	1.9	1.53	3.27	0.00	11.35	10.0
18	**1**	0.97	285	5.28	1	0.3	1.55	1.47	0.00	9.27	1.9
19	**1**	0.90	280	5.37	4	2.9	2.35	0.68	0.00	9.30	18.7
20	**1**	1.25	330	2.70	2	3.1	2.55	1.32	0.00	7.82	23.4
21	**1**	2.08	385	4.63	2	3.9	3.65	1.23	35.18	11.60	20.4
22	**1**	1.88	390	3.38	2	2.8	4.60	0.93	6.02	10.80	15.6
23	**1**	1.67	381	3.30	2	5.9	5.83	1.68	0.00	12.48	28.4
24	**1**	1.70	380	2.22	2	3.7	4.57	2.28	0.00	10.77	20.8
25	**1**	1.68	376	2.55	1	1.9	3.72	0.93	5.78	8.89	12.9
26	**1**	1.25	260	4.47	2	4.0	2.10	1.10	0.00	8.92	26.6
27	**1**	1.98	375	3.97	1	3.4	2.62	2.67	1.85	11.23	18.0
28	**1**	2.12	410	2.42	1	2.2	2.80	1.03	15.83	8.37	15.9
29	**1**	1.80	415	2.00	1	3.3	5.28	1.58	0.00	10.67	18.4
30	**1**	1.47	414	2.67	2	5.5	4.00	3.68	0.00	11.82	27.9
31	**1**	1.75	473	4.27	2	5.8	3.93	1.25	0.00	11.20	31.0
32	**1**	1.53	345	7.35	3	10.5	3.80	4.53	34.18	17.22	36.5
33	**1**	1.58	342	6.03	1	1.0	2.25	1.30	0.00	11.17	5.5
34	**1**	1.83	430	3.58	3	5.3	3.48	2.25	0.00	11.15	28.8
Min		**0.72**	**218**	**2.00**	**1.0**	**0.3**	**1.17**	**0.32**	**0.00**	**5.68**	**1.9**
Max		**2.12**	**473**	**7.35**	**4.0**	**10.5**	**5.83**	**4.53**	**35.18**	**17.22**	**83.7**
Avg		**1.33**	**311**	**3.87**	**2.0**	**4.7**	**2.56**	**1.49**	**4.21**	**9.26**	**32.2**
SD		**0.40**	**72**	**1.19**	**0.8**	**2.5**	**1.28**	**0.92**	**9.94**	**2.39**	**20.0**

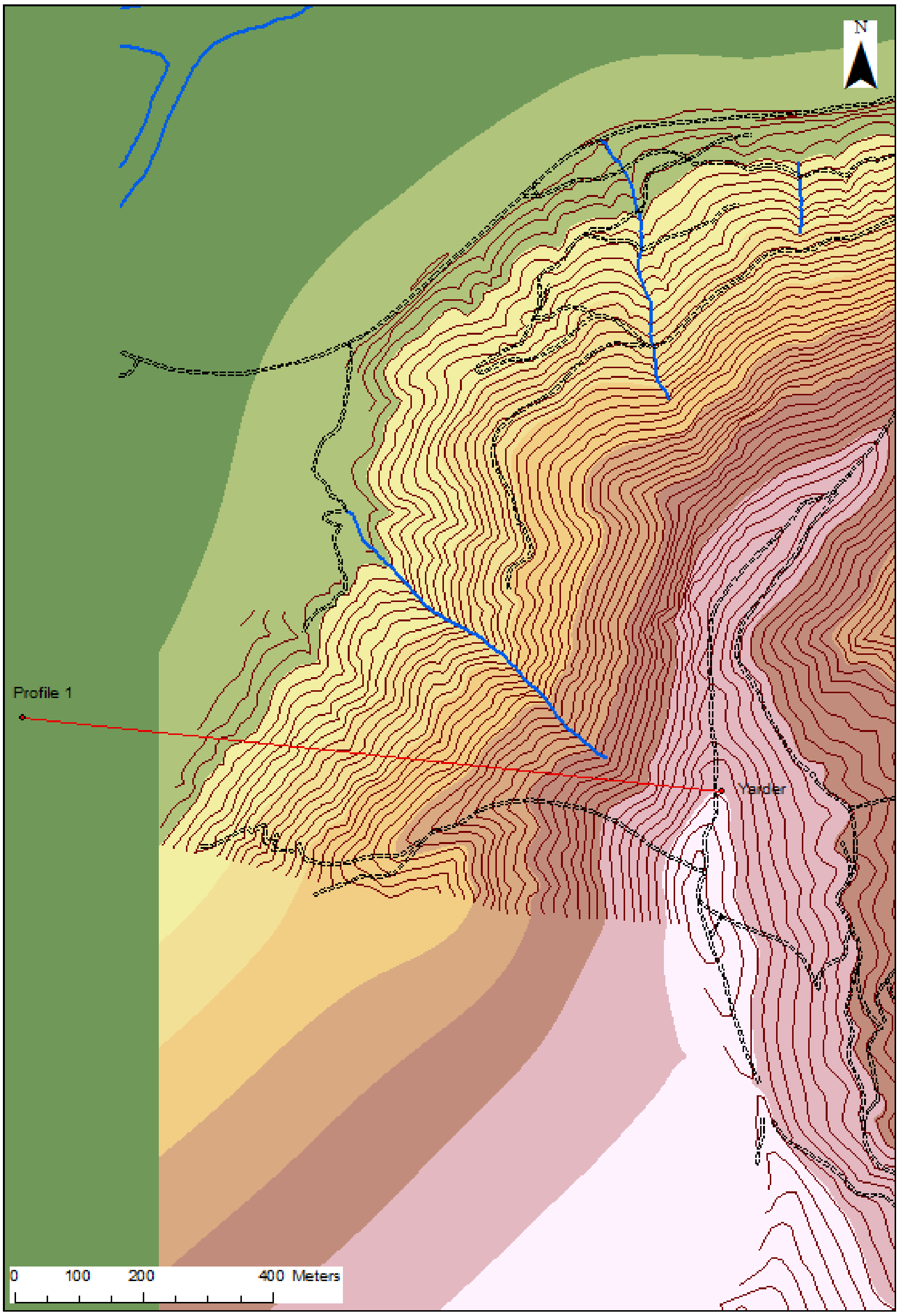


Figure 5.34: The ArcMap 10 meter contour elevation extracted profile for payload analysis of the yarding corridor observed during the operation at study site six in Marlborough.

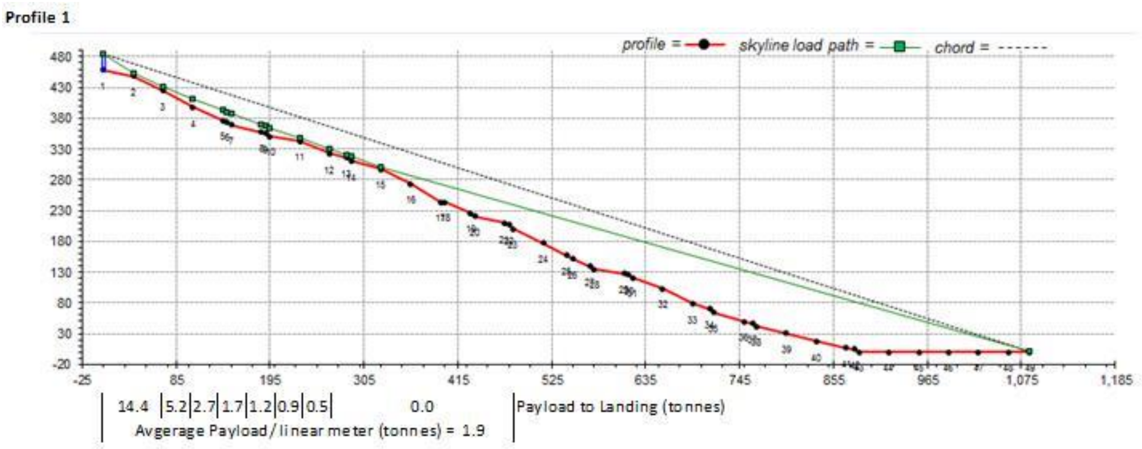


Figure 5.35: SkylineXL profile and payload analysis results for the North Bend Bridled operation at study site six in Marlborough.

Cycles one through 14 exceeded the safe working load (21.3 tons, 209.0 kN) on four of the cycles (Figure 5.36). The more than five minute delay observed between cycle eight & nine was due to a rope wrap issue that had to be resolved before outhaul in cycle nine (i.e. the rigging was sent out part way and then brought back to landing which untangled the ropes). Delays associated with cycles 11, 13 and 14 were due to difficulty landing the rigging at the end of the outhaul component. The difficulty was due to the fact that the crew was reaching the limits of their setup, and eventually shifted the haulback blocks after cycle 14.

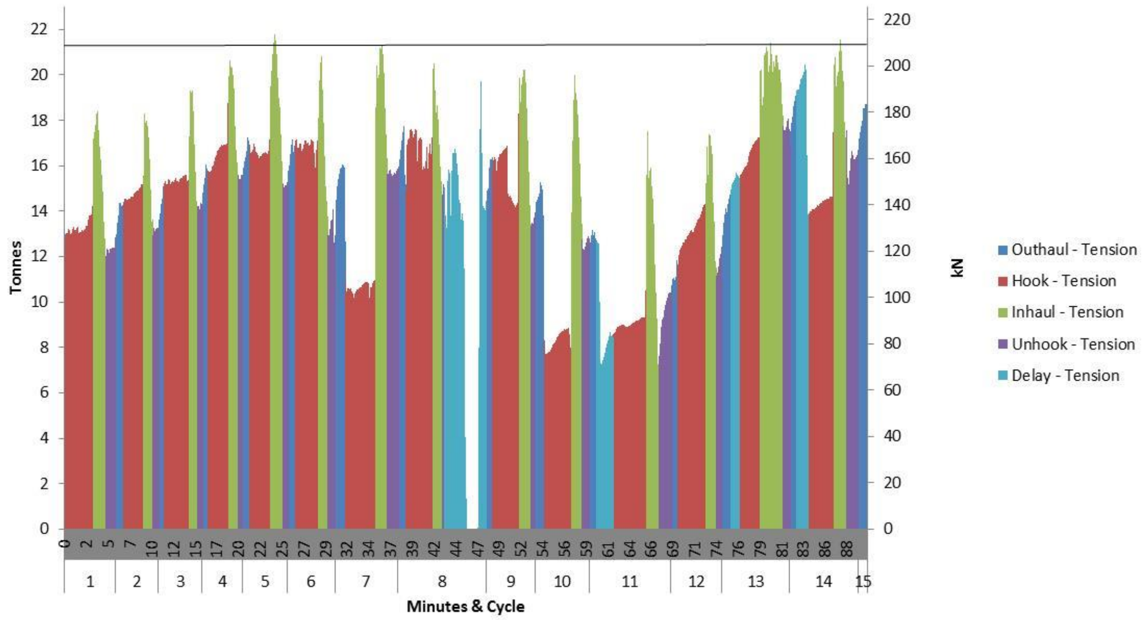


Figure 5.36: Skyline tensions for study site six, profile one, cycles 1-14 North Bend Bridled configuration.

During cycles 15-19 skyline tension increased for all elements of the cycles compared to earlier cycles, where all except for cycle 15 exceeded the safe working load (Figure 5.37). The extraction distance was again gradually increasing as it approached mid-span, so too was the lateral offset due to bridling. The hook element time and tensions increased, as a result of the increased lateral yarding distance. Breakout appeared to be getting more difficult and so were issues during inhaul with a blind lead area that wasn't yarded across in prior cycles. The skyline drum slipped at a tension of 27 tons, during inhaul of cycle 19 which generated enough of a shock load (8 tons) to knock the tension monitor off the skyline.

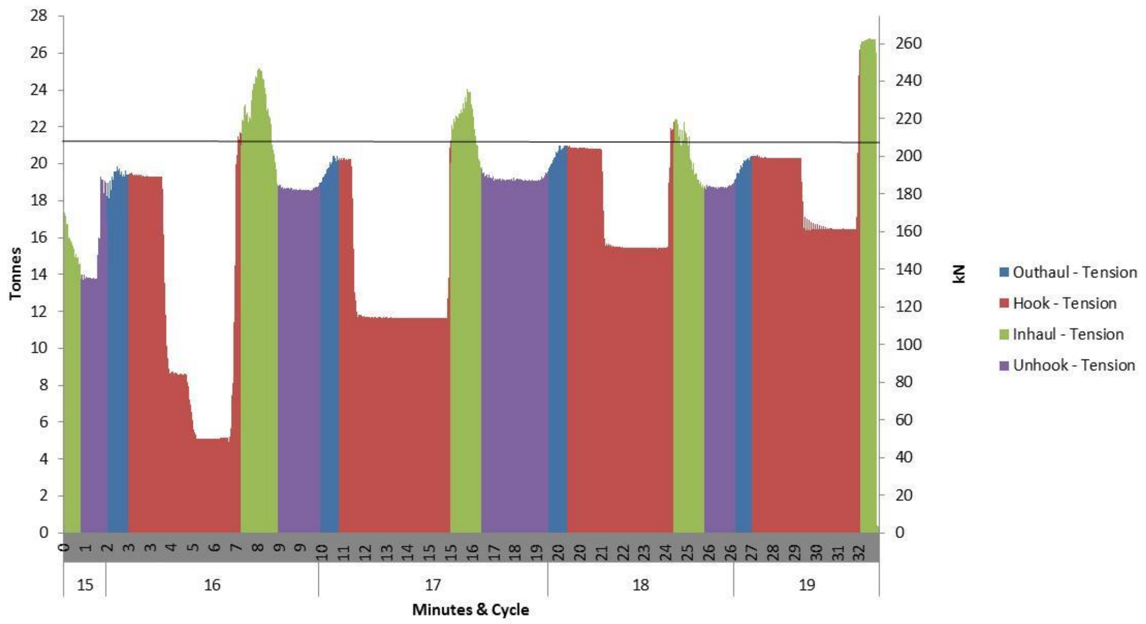


Figure 5.37: Skyline tensions for study site six, profile one, cycles 15-19, North Bend Bridled configuration.

Yarding resumed on the second day of observation with cycles 20 and 21 (Figure 5.38). The long delay associated with the start of cycle 21 was due to shifting haulback blocks to again extend the yarding and lateral yarding distances.

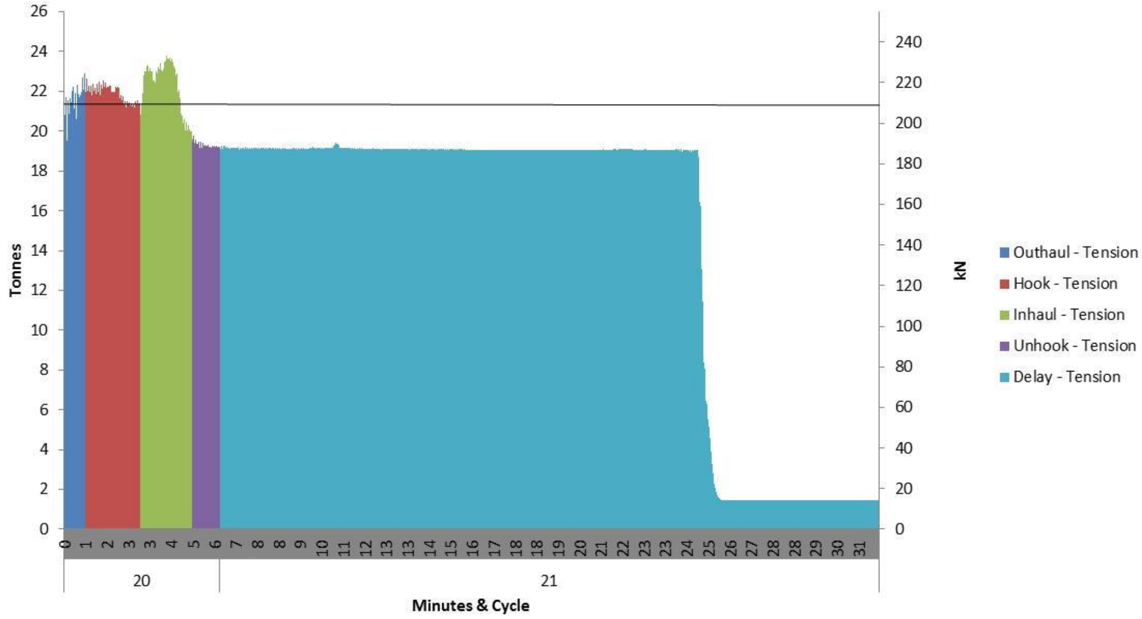


Figure 5.38: Skyline tensions for study site six, profile one, cycles 20 & 21, North Bend Bridled configuration.

The five minute delay at end of cycle 21 was due to researchers reconnecting the carriage mounted GPS unit which was knocked off during inhaul due to the carriage collision with the ground in the blind lead area of the profile (Figure 5.39). Delays associated with cycle 22 & 25 occurred during inhaul, when again there was poor clearance over the blind lead and drags became stuck (e.g. one stem had to be unchoked during cycle 25). The delay at the end of cycle 26 was due to changing chokers on the butt-rigging at the landing. The delay before outhaul of cycle 28 was due to shifting of haulback blocks.

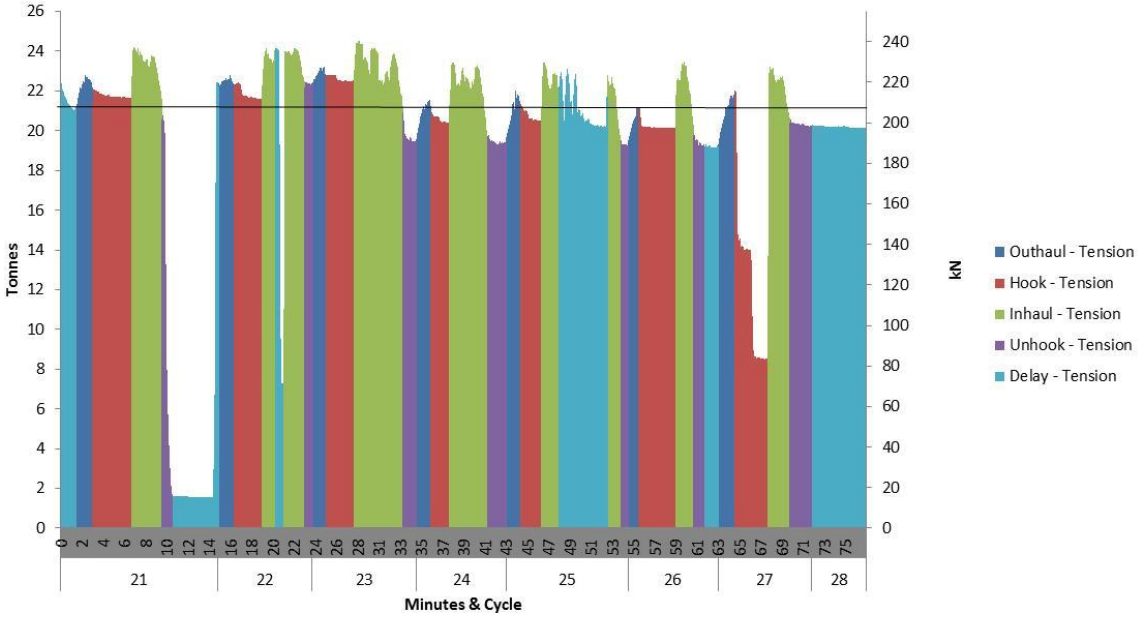


Figure 5.39: Skyline tensions for study site six, profile one, cycles 21-28, North Bend Bridled configuration.

The delay in cycle 32 was due to 30 minute lunch break initiated after stems were hooked (Figure 5.40). Maximum tensions during inhaul again continued to exceed the safe working load each cycle.

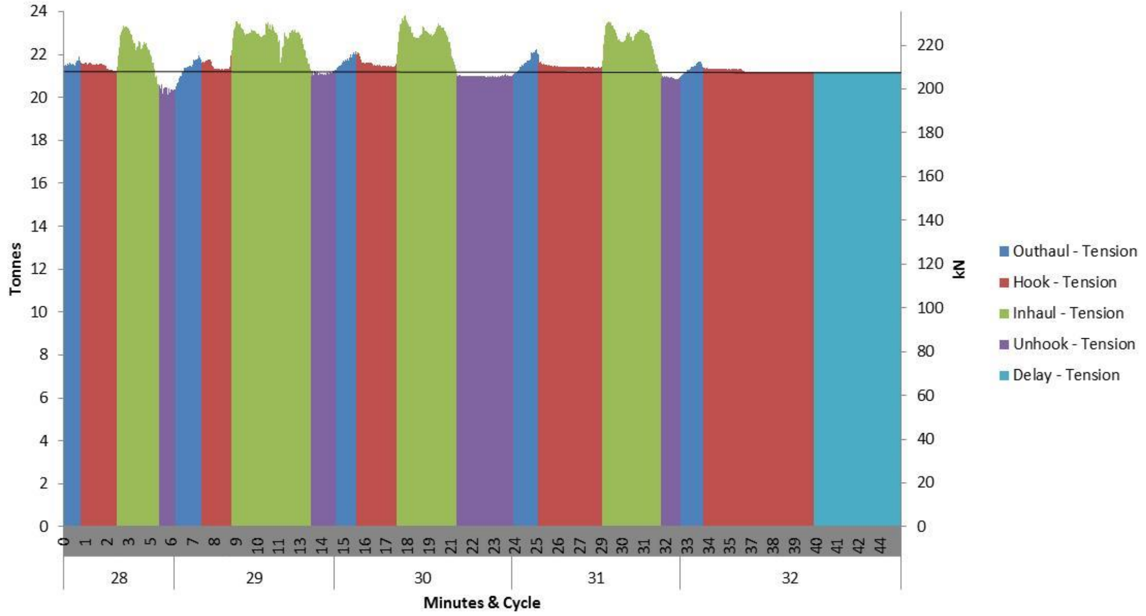


Figure 5.40: Skyline tensions for study site six, profile one, cycles 28-32, North Bend Bridled configuration.

The last cycles observed had high skyline pretension which were nearly equal to the safe working load, apparent by the unhook tensions (Figure 5.41). It is interesting to note that there is little difference in tension due to different elements of the cycle, and very little variation in tension. These variable but high tensions can be attributed to the force generated by the off-setting of haulback blocks, which are pulling the carriage and skyline to the side. The tensions were very different in behavior from the first cycles observed, which was likely due to the shifting of tail blocks (further out the span) after cycle 28 in combination with the poor deflection in this setup (3.8%).

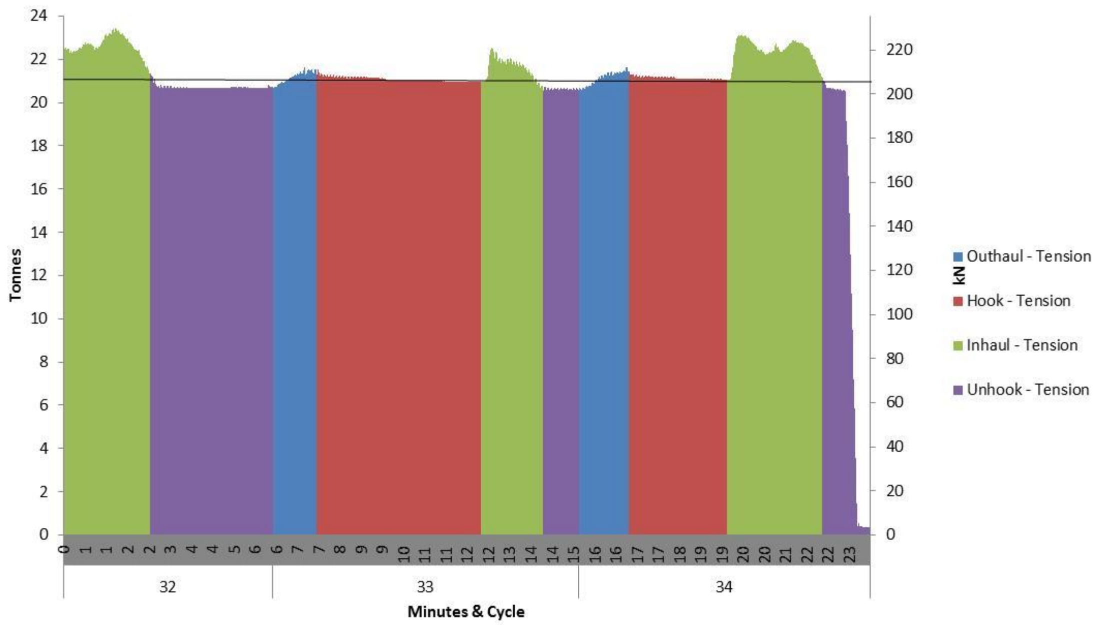


Figure 5.41: Skyline tensions for study site six, profile one, cycles 32-34, North Bend Bridled configuration.

5.4.7 Study Site 7

The operation at study site seven in Nelson (Figure 5.42; Figure 5.43), was observed for one day across two spans, in which 23 cycles were recorded (Table 5.9). The corridors were located next to one another with relatively smooth terrain that was concave in shape. North Bend was the only configuration in use at this site and provided the necessary lift of stems over the incised gulley located at mid-span. With an average cycle time (7.70 minutes) and volume (5.4 m^3) the configuration had an average production rate of 43.9 (m^3/PMH). Payload analysis indicated that the limiting payload (5.6 and 6.7 tons) was located at mid-span for profiles one and two, respectively (Figure 5.44). The yarder operator had a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during none of the cycles (0% frequency).

Figure 5.42: North Bend operation at study site seven in Nelson, viewed from the anchor position.

Table 5.9: Summary of the 23 observed cycle times and variables at study site seven in Nelson.

Cycle (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	AvgVol (m^3)	PayloadE	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	0.77	308	3.90	5	4.9	2.7	1.82	2.20	1.85	0.00	8.72	33.7
2	1.05	319	2.42	5	5.7	2.7	2.11	2.05	2.18	0.00	7.70	44.4
3	0.77	308	2.02	3	4.6	2.7	1.70	1.88	2.05	0.00	6.72	41.1
4	0.95	324	3.50	5	4.0	2.7	1.48	1.75	2.87	0.00	9.07	26.5
5	0.65	330	4.82	5	4.6	2.7	1.70	2.25	2.60	0.00	10.32	26.8
6	0.90	342	3.28	5	6.1	2.7	2.26	2.10	1.55	0.00	7.83	46.7
7	0.90	349	1.82	5	7.0	2.7	2.59	2.15	1.57	0.00	6.43	65.3
8	0.90	348	1.92	3	4.8	2.7	1.78	1.82	1.58	0.00	6.22	46.3
9	0.97	364	2.72	4	5.4	2.7	2.00	1.98	2.93	0.00	8.60	37.7
10	1.05	374	1.88	5	5.9	2.7	2.19	2.42	1.50	0.00	6.85	51.7
11	1.12	202	4.37	3	2.9	7.3	0.40	1.35	2.22	45.72	9.05	19.2
12	0.65	195	4.98	5	5.2	7.3	0.71	1.68	1.40	1.33	8.72	35.8
13	0.68	216	6.30	6	4.9	7.3	0.67	1.63	3.90	0.00	12.52	23.5
14	0.75	223	2.92	5	4.3	7.3	0.59	1.45	1.35	0.00	6.47	39.9
15	0.53	233	2.85	5	5.3	7.3	0.73	1.27	1.18	0.00	5.83	54.5
16	0.87	246	3.15	5	5.1	7.3	0.70	1.90	1.38	1.65	7.30	41.9
17	0.67	252	3.37	6	8.4	7.3	1.15	2.05	0.83	1.05	6.92	72.9
18	0.72	262	2.45	5	7.3	7.3	1.00	2.27	1.80	0.00	7.23	60.6
19	0.67	267	2.55	4	5.1	7.3	0.70	1.78	1.40	0.00	6.40	47.8
20	0.70	272	3.18	4	4.9	7.3	0.67	1.22	2.58	0.00	7.68	38.3
21	0.70	285	3.98	5	7.0	7.3	0.96	1.42	1.38	0.00	7.48	56.1
22	0.75	285	3.00	5	5.5	7.3	0.76	1.83	1.35	0.00	6.93	47.6
23	0.62	291	2.67	5	5.4	7.3	0.74	1.65	1.25	0.00	6.18	52.4
Min	**0.53**	**195**	**1.82**	**3.0**	**2.9**	**2.7**	**0.40**	**1.22**	**0.83**	**0.00**	**5.83**	**19.2**
Max	**1.12**	**374**	**6.30**	**6.0**	**8.4**	**7.3**	**2.59**	**2.42**	**3.90**	**45.72**	**12.52**	**72.9**
Avg	**0.80**	**287**	**3.22**	**4.7**	**5.4**	**5.3**	**1.28**	**1.83**	**1.86**	**2.16**	**7.70**	**43.9**
SD	**0.16**	**53**	**1.11**	**0.8**	**1.2**	**2.3**	**0.66**	**0.34**	**0.72**	**9.51**	**1.55**	**13.3**

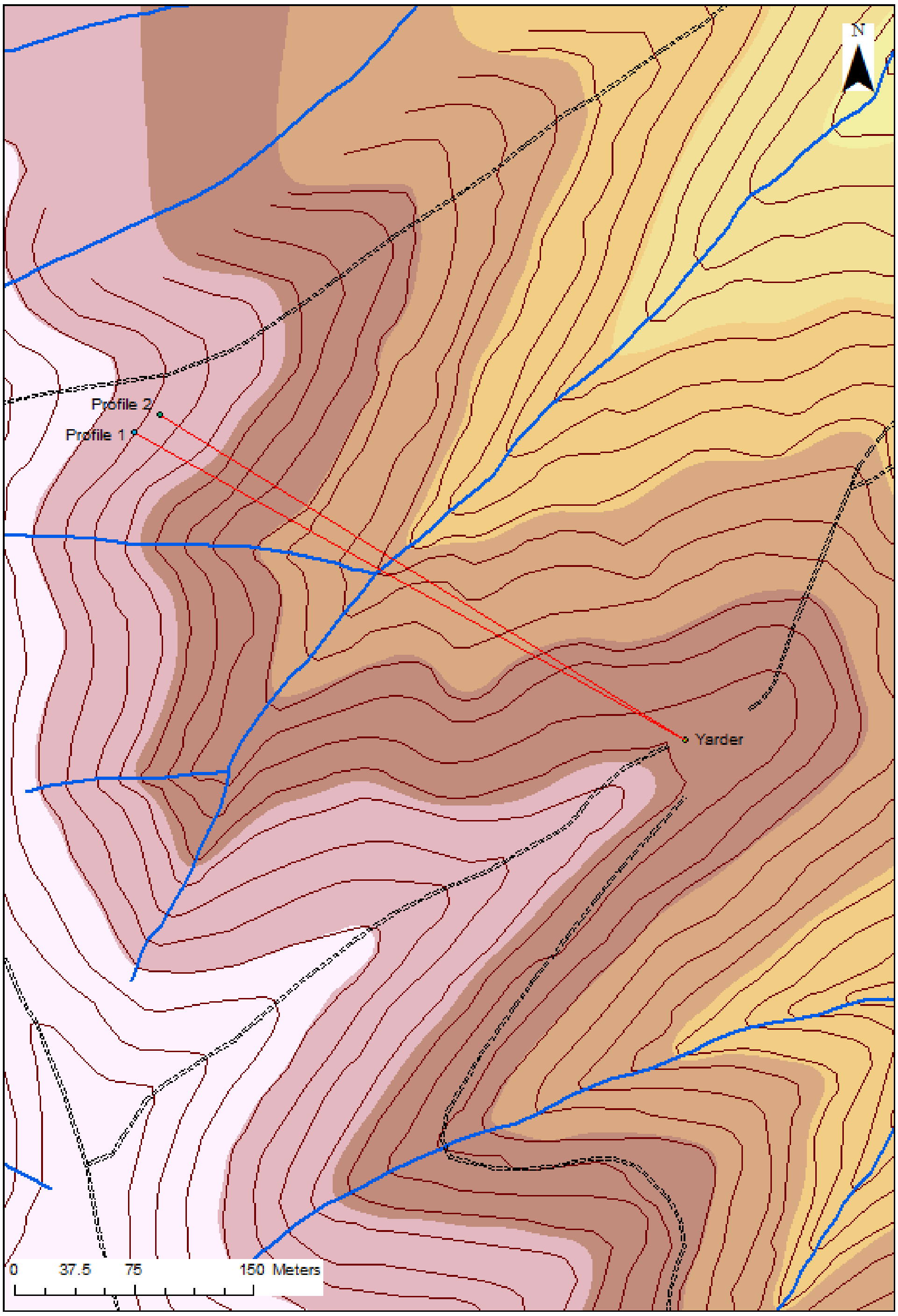
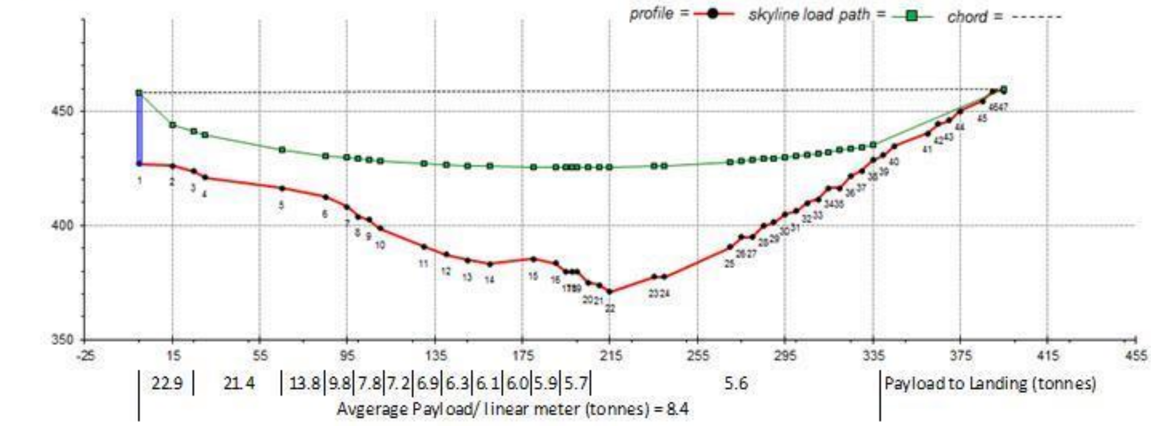


Figure 5.43: The ArcMap 10 meter contour elevation extracted profiles for payload analysis of each yarding corridor observed during the operation at study site seven in Nelson.

Profile 1



Profile 2

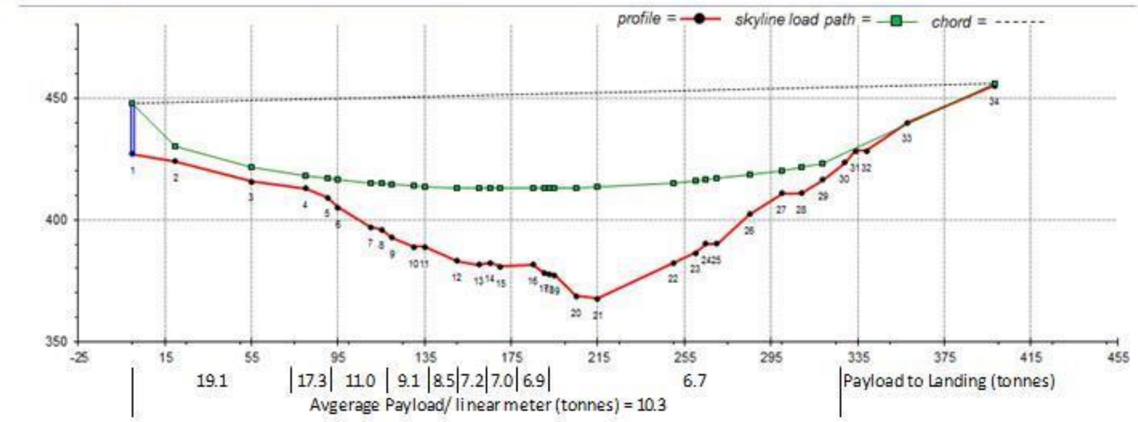


Figure 5.44: SkylineXL profile and payload analysis results for the North Bend operation at study site seven in Nelson.

Cycles 1-10 were recorded in just over an hour and all took place along profile one which had (Figure 5.45). Safe working load for the skyline (21.3 tons, 209.0 kN) was not exceeded as maximum skyline tension was 20.8 tons during inhaul of cycle 10, and pretension in the skyline noted from the unhook component (purple color) was approximately 3 tons for this setting. The 10 cycles were all pulled from the back face with the latter ones close to the tail hold where the tension monitor was located, which may explain the higher tensions.

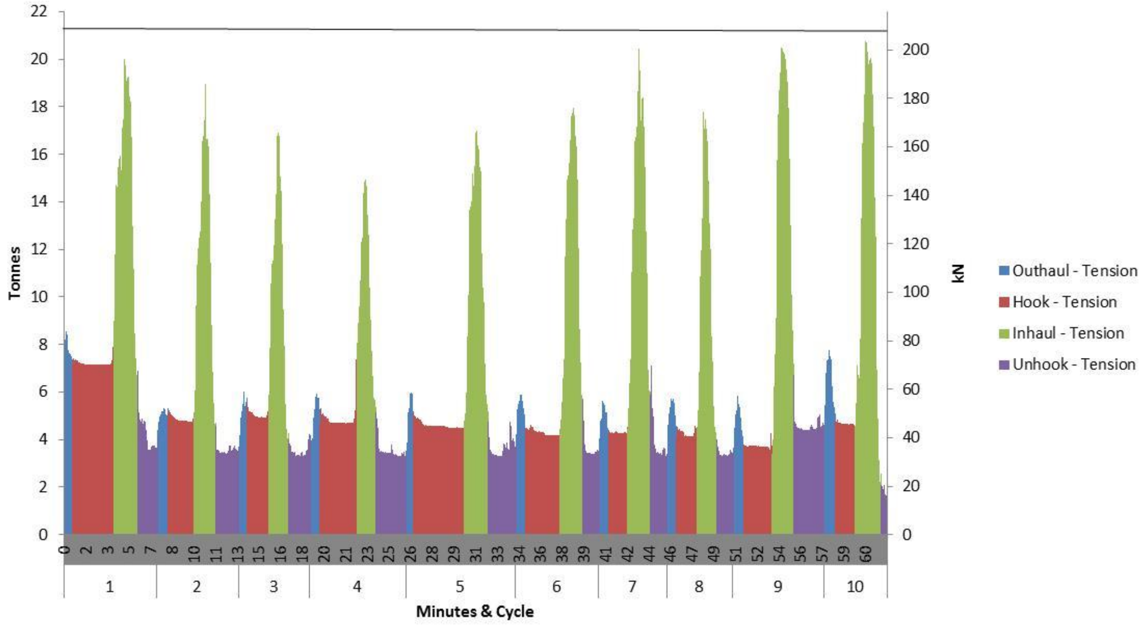


Figure 5.45: Skyline tensions for study site seven, profile one, cycles 1-10, North Bend configuration.

Cycles 11-23 were all observed along profile two (Figure 5.46). These cycles were also pulled from the back face as in corridor one, but yarding started (cycles 11-14) from the incised gulley around mid-span and worked progressively further toward the tail hold. Note the longer hook time associated with these first cycles as the breakerouts had to climb in an out of the gulley to attach chokers. Also of interest and highlighting the difficulty of yarding from the 2m incised gulley, cycle 13 had a peak tension that was 4 tons greater than other cycles in the profile, due to a hang-up during breakout. However, the safe working load was not exceeded and the peak tensions were much lower than the first span, most likely because deflection increased (from 8.4 to 10.1%). Delays shown in cycles 12, 16 & 17 were 1.3, 1.6 & 1.1 minutes respectively. These three delays occurred at the end of inhaul before unhooking, and were associated with the difficulty of landing or having to re-land the stems before unhooking; the yarder operator claimed the weight of haulback was trying to pull stems back over the edge of the landing, which is a common issue associated with the North Bend configuration.

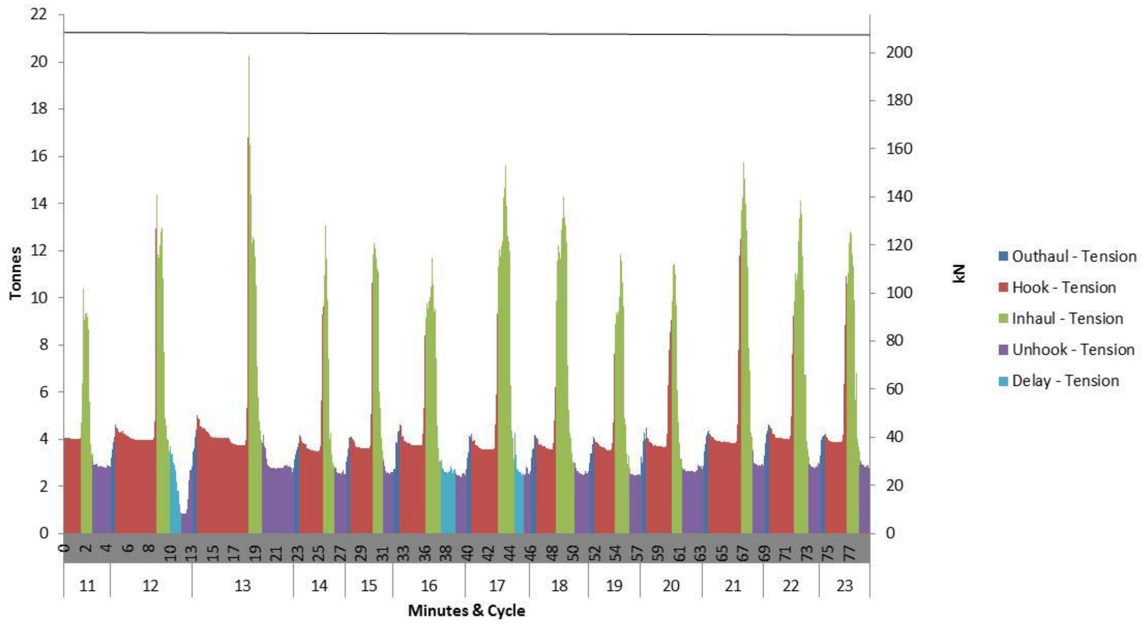


Figure 5.46: Skyline tensions for study site seven, profile two, cycles 11-23, North Bend configuration.

5.4.8 Study Site 8

The operation at study site eight in Otago (Figure 5.47; Figure 5.48), was observed for two days across three spans, in which 42 cycles were recorded (Table 5.10). The corridors were located next to one another and were all concave in shape, but had broken terrain due to occasional rock bluffs. Acme Slackline was the main configuration in use at this site, but the third span (cycles 28-42) allowed a steep enough chord slope for the Acme Shotgun configuration to be employed. The average cycle time (5.57 minutes) and volume (3.2 m^3) led to an average productivity of 36.1 (m^3/PMH). Payload analysis indicated that the limiting payload (3.1, 2.4 and 2.4 tons) was located at mid-span for profiles one through three, respectively. The yarder operator had a skyline tension monitor with display unit and the safe working load (21.3 tons) was exceeded during 24 of the cycles (57% frequency).

Figure 5.47: Acme Slackline & Acme Shotgun operation at study site eight in Otago, viewed from the anchor position.

Table 5.10: Summary of the 42 observed cycle times and variables at study site eight in Otago.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m³)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m³/PMH)
1	1	0.58	223	2.08	2	4.9	1.33	0.37	1.97	4.37	67.7
2	1	0.62	227	2.87	2	2.4	1.43	0.47	1.20	5.38	26.4
3	1	0.67	232	1.55	2	4.2	1.73	0.58	0.67	4.53	55.8
4	1	0.72	237	1.77	2	3.4	1.57	0.45	0.00	4.50	44.9
5	1	0.72	249	3.33	2	1.4	1.85	0.78	1.20	6.68	12.7
6	1	0.59	284	2.52	2	0.7	1.32	0.57	11.88	5.00	8.0
7	1	0.40	284	2.97	2	2.7	1.07	0.63	5.55	5.08	32.1
8	1	0.53	184	6.45	2	1.9	1.30	0.78	0.00	9.07	12.3
9	1	0.60	189	3.45	2	3.7	1.42	0.45	0.00	5.92	37.0
10	1	0.55	212	2.38	2	3.1	1.65	0.77	0.00	5.35	35.2
11	1	0.52	212	3.03	2	3.1	1.58	0.43	0.00	5.57	33.4
12	1	0.63	223	2.85	2	2.0	1.43	0.65	0.00	5.57	21.6
13	1	0.62	230	5.38	2	3.3	1.08	0.67	0.00	7.75	25.9
14	2	0.53	159	2.62	3	1.8	1.35	0.57	0.00	5.07	21.6
15	2	0.53	166	4.05	3	3.1	1.65	0.40	0.00	6.63	27.6
16	2	0.50	175	2.60	2	2.5	1.12	0.52	0.00	4.73	32.1
17	2	0.57	179	3.73	3	3.6	1.23	0.73	0.00	6.27	34.2
18	2	0.58	184	2.77	2	3.3	1.15	0.40	0.00	4.90	40.2
19	2	0.87	183	3.07	2	1.8	1.07	0.58	0.00	5.58	19.6
20	2	0.53	187	2.35	2	5.1	1.55	0.35	0.00	4.78	64.5
21	2	0.55	198	5.48	2	3.9	1.50	0.30	0.00	7.83	29.9
22	2	0.52	197	3.45	2	4.4	1.45	0.37	0.00	5.78	45.5
23	2	0.55	192	5.30	2	0.7	1.28	0.32	0.00	7.45	6.0
24	2	0.63	207	2.17	2	3.0	1.40	0.37	0.00	4.57	39.4
25	2	0.62	209	3.40	2	3.0	1.35	0.32	0.00	5.68	31.2
26	2	0.72	217	4.62	3	3.2	1.58	0.45	3.18	7.37	26.2
27	2	0.72	227	3.07	2	3.4	1.78	0.33	0.00	5.90	34.6
28	3	0.47	122	3.53	2	5.0	1.50	0.32	0.20	5.82	51.5
29	3	0.27	124	3.15	2	2.4	1.45	0.12	0.52	4.98	28.5
30	3	0.18	127	5.18	3	4.8	1.48	1.02	0.00	7.87	36.2
31	3	0.20	132	2.62	3	2.5	1.08	0.67	0.18	4.57	32.8
32	3	0.30	130	1.97	2	4.0	1.12	0.35	0.13	3.74	64.1
33	3	0.27	141	2.83	2	3.9	1.57	0.45	0.15	5.12	45.5
34	3	0.23	146	2.55	2	4.2	1.37	0.52	0.15	4.67	53.5
35	3	0.27	144	3.10	2	3.0	1.17	0.48	0.17	5.02	35.6
36	3	0.25	146	4.57	1	2.5	0.97	0.82	0.15	6.61	22.4
37	3	0.37	155	2.38	2	4.1	1.20	0.38	0.15	4.33	57.0
38	3	0.22	153	2.98	2	4.1	1.30	0.48	0.08	4.98	49.5
39	3	0.33	162	3.95	2	2.3	1.07	0.40	0.17	5.75	24.2
40	3	0.32	160	2.47	2	3.8	1.77	0.52	0.13	5.07	44.5
41	3	0.25	165	2.33	2	4.1	1.42	0.43	6.85	4.43	54.9
42	3	0.33	170	1.57	2	3.0	1.17	0.42	0.17	3.49	51.6
Min		**0.18**	**122**	**1.55**	**1.0**	**0.7**	**0.97**	**0.12**	**0.00**	**3.49**	**6.0**
Max		**0.87**	**284**	**6.45**	**3.0**	**5.1**	**1.85**	**1.02**	**11.88**	**9.07**	**67.7**
Avg		**0.49**	**187**	**3.20**	**2.1**	**3.2**	**1.38**	**0.50**	**0.83**	**5.57**	**36.1**
SD		**0.17**	**41**	**1.13**	**0.4**	**1.1**	**0.22**	**0.18**	**2.25**	**1.21**	**15.2**

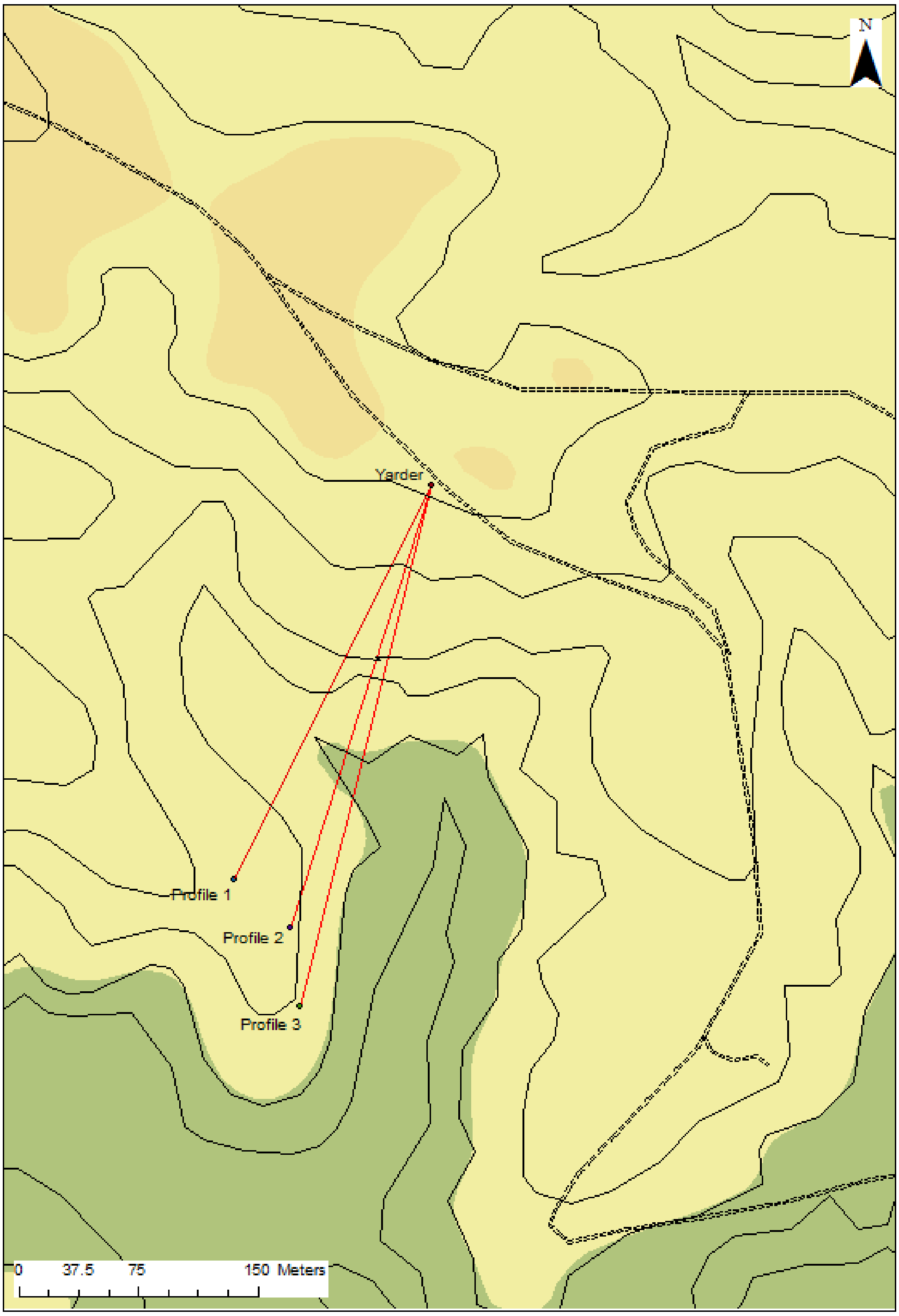


Figure 5.48: The ArcMap 20 meter contour elevation extracted profiles for payload analysis of each yarding corridor observed during the operation at study site eight in Otago.

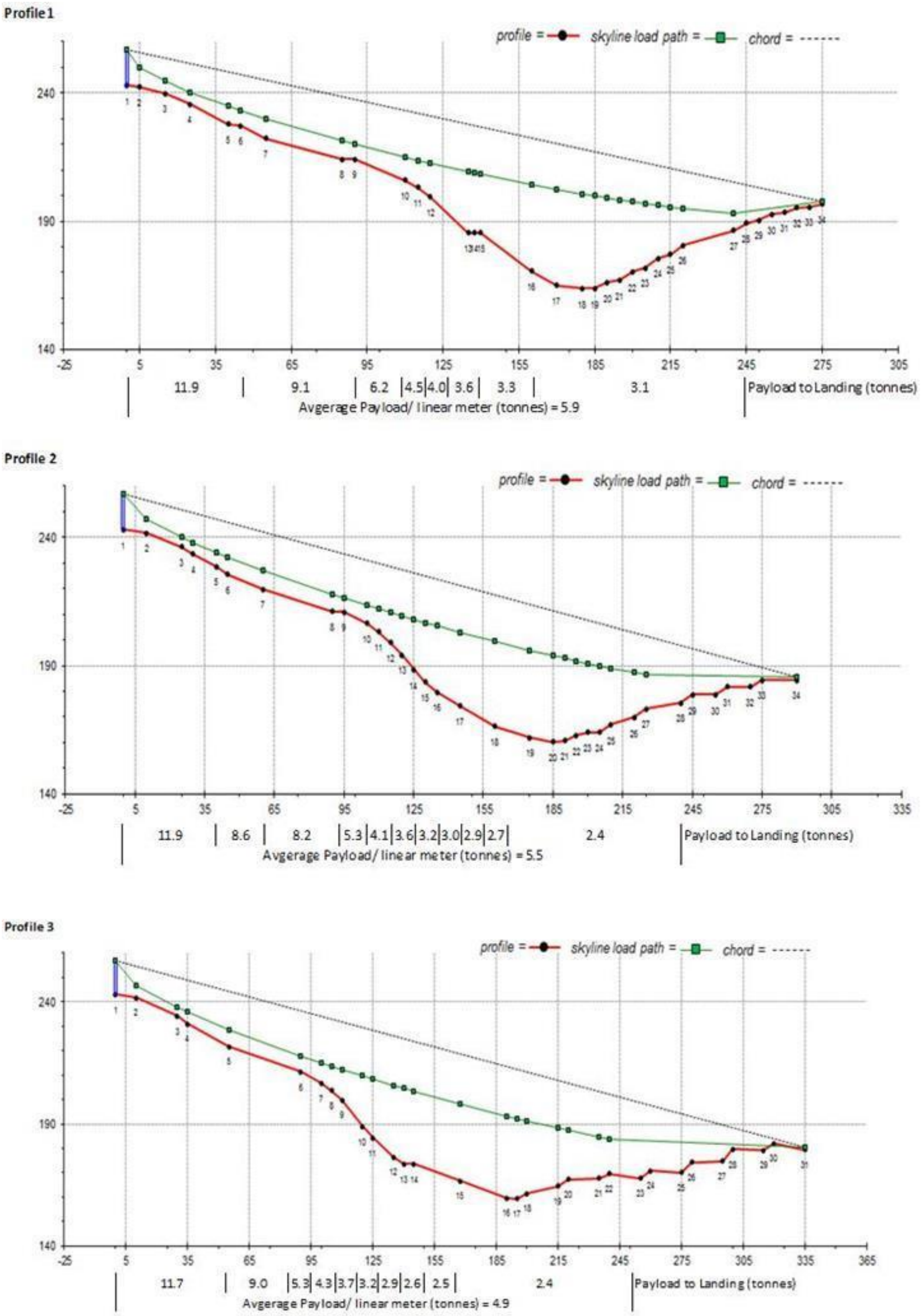


Figure 5.49: SkylineXL profile and payload analysis results for the Acme Slackline and Acme Shotgun operation at study site eight in Otago.

In the first profile (Figure 5.50), cycles one, three, five & 10 have delays during inhaul due insufficient log clearance (difficult rock bluff). There are high tensions generated during these delays as the carriage has to be stopped and clamped to the skyline, while the mainline is pulled through the carriage to raise the logs. After the logs have reached a desired height the carriage clamps the mainline and unclamps the skyline, and inhaul resumes. Cycle 6 & 7 had large delays associated with transporting fuel and other equipment along the corridor to assist in starting the anchor machine, which had mechanical problems but was required for an upcomming line shift to corridor number two. The skyline was adjusted during these cycles which is why there is a noticeable tension incease (especially during the hook element) for the remaining cycles. The skyline safe working load (18.6 tonnes, 182.3 kN) was exceeded during nine of the 13 cycles.

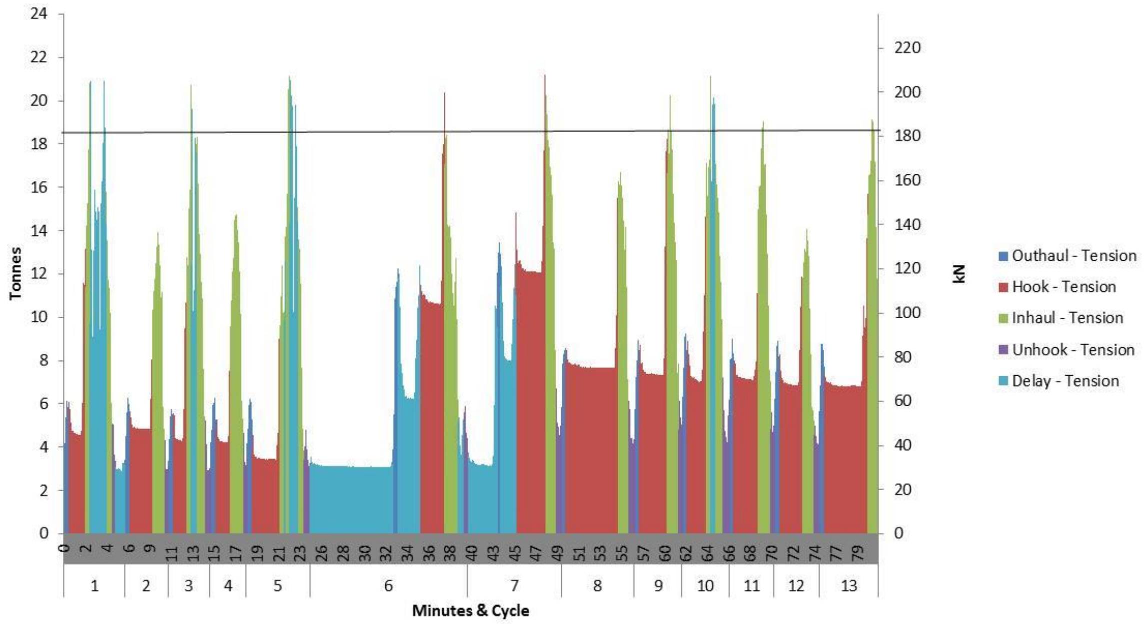


Figure 5.50: Skyline tensions for study site eight, profile one, cycles 1-13, Acme Slackline configuration.

In the second profile (Figure 5.51) cycles 14-27, better log clearance due to topography resulted in less delays during inhaul. Cycle 26 includes a personal delay where the yarder operator had to stop the carriage during inhaul to move a vehicle on the landing. The safe working load was only exceeded during two of the 14 cycles.

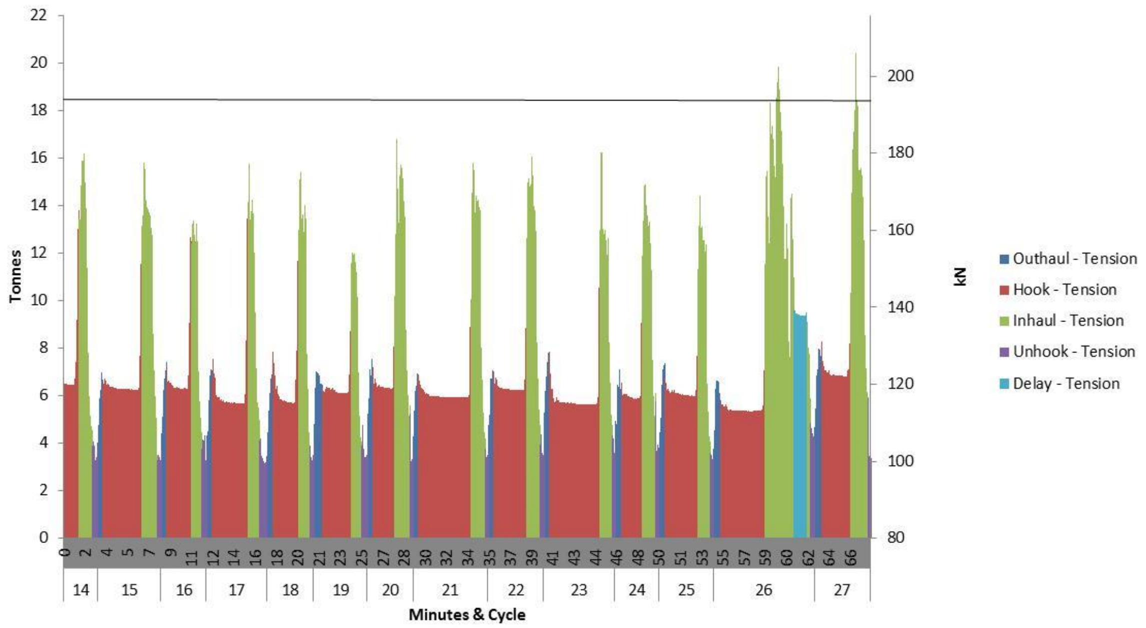


Figure 5.51: Skyline tensions for study site eight, profile two, cycles 14-27, Acme Slackline configuration.

In the third profile (Figure 5.52) cycles 28-42 deflection was reduced to 6.2% each cycle was extracted in close proximity to mid-span. The combination of reduced deflection and carriage position caused the safe working load to be exceeded on all but two of the cycles. Another rock bluff caused similar delays as observed during the first profile, but occurred nearly every cycle. However, there is a noticeable difference in outhaul time as indicated by the dark blue shaded area. The delay during cycle 41 was due to adjusting the guyline tensions.

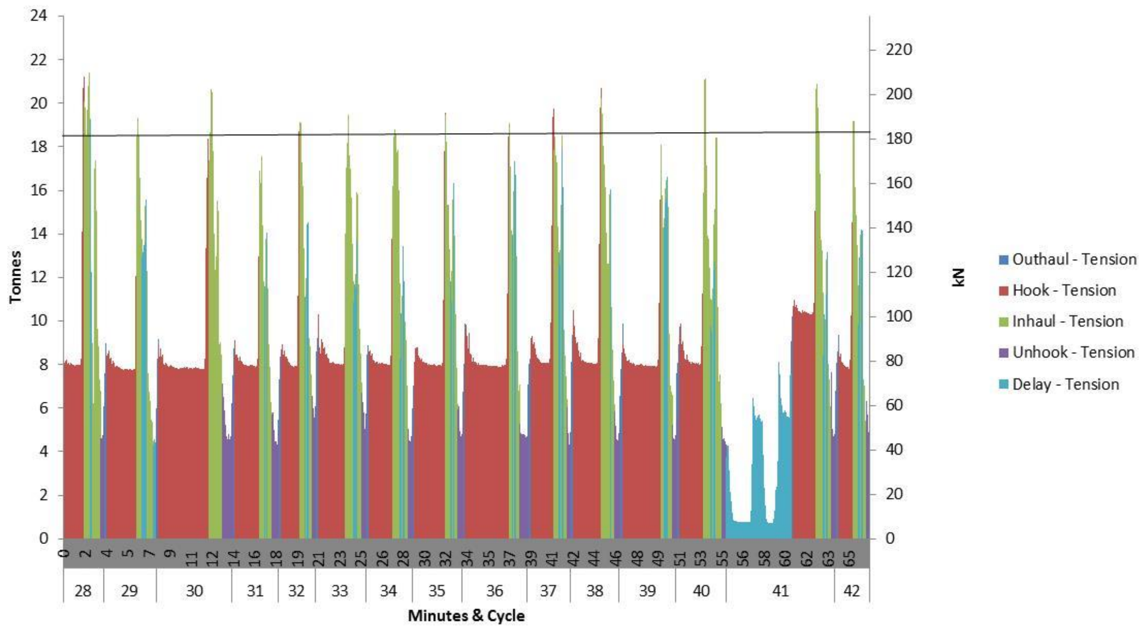


Figure 5.52: Skyline tensions for study site eight, profile three, cycles 28-42, Acme Shotgun configuration.

5.4.9 Productivity Analysis

5.4.9.1 Cycle and Element Times

The results from each study site were combined to create a database of cycles by configuration with their corresponding measured variables. The average cycle times and their element times as a percentage of cycle time were summarized (Table 5.11). North Bend Bridled had the largest average delay-free cycle time of 8.96 minutes, with 43% of its cycle consumed by the hook element (3.87 minutes). The Falcon Shotgun had the smallest average delay-free cycle time of 2.54 minutes, with 38% of its cycle consumed by the inhaul element (0.97 minutes).

Table 5.11: Average element times and the percentage of productive time for each element grouped by rigging configuration.

	North Bend		North Bend Bridled		Acme Shotgun		Acme Slackline		Falcon Shotgun		Falcon Slackline	
Cycle Element	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**
Outhaul	1.06	13	1.32	15	0.28	6	0.61	9	0.41	16	0.54	18
Hook	3.35	42	3.87	43	3.01	59	3.76	57	0.84	33	1.18	40
Inhaul	1.91	24	2.42	27	1.31	26	1.63	25	0.97	38	1.08	37
Unhook	1.67	21	1.35	15	0.49	10	0.55	8	0.31	12	0.14	5
Delay-Free Cycle Time	7.99		8.96		5.10		6.55		2.54		2.93	

There are some general characteristics that can be highlighted from these results:

1. The variations of each configuration (e.g. Acme Shotgun & Acme Slackline) perform very similar in comparison to other configurations (e.g. Acme Shotgun vs North Bend).
2. The shotgun configuration whether an Acme or Falcon carriage is used, has a comparatively shorter outhaul time and cycle time than the Slackline configuration with the same carriage.
3. The configurations using the Falcon carriage have a quick hook element compared to other configuration as they do not require logs to be choked.
4. Unhook times are greatest when a person is required to unhook chokers as observed during North Bend and North Bend Bridled (1.67 & 1.35 minutes), compared to electronic chokers as observed during Acme Shotgun and Acme Slackline (0.49 and 0.55 minutes), compared to a grapple carriage as observed during Falcon Shotgun and Falcon Slackline (0.31 and 0.14 minutes).

5.4.9.2 Regression Equations

In order to determine how conditions affected productive cycle time of each configuration, regression analysis was performed using the measured variables from each cycle. The range of these values recorded during the time study and their averages were summarized (Table 5.12). Through simple observation of this table we can note some differences between the configurations, like their average distance and cycle volume which help to explain some of the differences in cycle time and production rates.

Table 5.12: Representative values of the variables recorded for each configuration during the study.

Independent Variables		North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Span (m)	Min	395	920	354	284	338	345
	Max	940	1100	354	335	602	364
	Average	577.8	1080.5	354.0	308.8	480.8	353.3
Chord Slope (%)	Min	-14	-43	-23	-21	-47	-27
	Max	1	-14	-23	-17	-30	-26
	Average	-4.3	-39.9	-23.0	-19.4	-37.9	-26.7
Deflection (%)	Min	5.2	3.8	6.2	4.2	5.7	5.9
	Max	10.1	5.1	6.2	6.9	6.05	7.4
	Average	8.0	3.9	6.2	6.1	5.9	6.3
Breakerouts (# men)	Min	2	2	2	1	0	0
	Max	3	3	2	4	0	0
	Average	2.5	2.1	2.0	2.5	0.0	0.0
Chokers (# in use)	Min	3	2	2	2	0	0
	Max	3	3	2	3	0	0
	Average	3.0	2.3	2.0	2.4	0.0	0.0
Chasers (# men)	Min	1	1	0	0	0	0
	Max	1	1	0	0	0	0
	Average	1	1	0	0	0	0
Distance (m)	Min	195	100	122	155	118	94
	Max	374	473	170	314	291	275
	Average	285.3	289.5	145.1	226.6	203.5	216.9
Pieces (#/cycle)	Min	2	1	1	1	1	1
	Max	6	4	3	11	3	4
	Average	4.2	1.9	2.1	2.4	1.5	1.4
Cycle Volume (m^3)	Min	2.9	0.3	2.3	0.7	0.3	0.2
	Max	9.3	9.4	5.0	9.1	4.4	5.8
	Average	5.9	4.6	3.6	4.3	2.1	2.2
Piece Size (m^3)	Min	1.2	2.4	1.5	1.5	1.4	1.6
	Max	2.4	2.4	1.5	2.1	2.4	1.6
	Average	1.6	2.4	1.5	1.8	1.5	1.6
Yarding Corridors		2	2	3	2	2	3
Cycles		33	37	15	49	65	54

In order to quantify the relationships between yarding time and site conditions so that we can predict production rates for future sites, regression equations were developed for each element of the yarding cycle and total cycle time. Variables are only included in these equations if their associated coefficient is significantly different from zero at an acceptable probability level. In this study variables were only included in the final predictive equation if their P-value was less than 0.01 (**) or between 0.05 and 0.01 (*). Regression equations also have an R^2 value known as the multiple correlation coefficient, which is a measure of fit between the observed time and the equations calculated time. An R^2 value of 100% indicates a perfect fit between the observed and predicted times. The individual equations, their R^2 value and the level of significance of each variable included in the model were calculated.

5.4.9.2.1 Outhaul

Outhaul time was found to be significantly influenced by distance and configuration, followed by span and to a lesser extent chord slope.

Outhaul time = -0.17441	R^2= 77.53%
+0.002326(Distance)	**
+0.000844(Span)	**
+0.004329(ChordSlope)	*
Configuration	**
+0.01461(North Bend)	
+0.07842(North Bend Bridled)	
-0.07858(Acme Shotgun)	
+0.08585(Acme Slackline)	
-0.12842(Falcon Shotgun)	

-0.02812(Falcon Slackline)

5.4.9.2.2 Hook

Hook time was found to be significantly influenced by piece size, configuration and by the number of pieces. In both cases increasing piece size and number of pieces increased the hook time.

Hook time = 0.7468		R^2= 66.58%
	+0.9000(PieceSize)	**
	+0.15435(Pieces)	*
	Configuration	**
	+0.5249(North Bend)	
	+0.6650(North Bend Bridled)	
	+0.5964 (Acme Shotgun)	
	+0.9514(Acme Slackline)	
	-1.5094(Falcon Shotgun)	
	-1.2283(Falcon Slackline)	

There are perhaps some hidden influences that are nested within configurations. For instance knowing the configuration does not tell us how many choker-setters were employed or how many chokers were used, and there is little variation within configurations in these two metrics. An additional equation was developed, which highlights this issue. Knowing only the number of choker-setters and the number of chokers used we have arrived at a similar fit

(R^2), but this equation shows how when using chokers, the number of chokers affects the time, and so do the number of choker-setters.

Hook time =	2.0303	R^2= 66.09%
	+0.7247(PieceSize)	**
	-0.3834(choker-setters)	*
	Chokers	**
	-2.1699((No Chokers)	
	+0.8106(2 Chokers)	
	+1.3593(3 Chokers)	

5.4.9.2.3 <u>Inhaul</u>

Inhaul was found to be significantly influenced by configuration, span, distance and chord slope much like outhaul. However it is more time consuming than outhaul because there is resistance from the load, which is why cycle volume was found to be statistically significant.

Inhaul time =	-0.2608	R^2= 67.16%
	+0.00937(Span)	**
	+0.019629(ChordSlope)	**
	+0.007232(Distance)	**
	+0.03859(CyclVol)	*
	Configuration	**
	-0.5773(North Bend)	

+0.0469(North Bend Bridled)

+0.503(Acme Shotgun)

+0.18157(Acme Slackline)

-0.02907(Falcon Shotgun)

-0.1251(Falcon Slackline)

5.4.9.2.4 *Unhook*

The unhook time was found to be significantly influenced by the number of pieces and the number of chokers, and whether or not these had to be unhooked by a person (chaser).

Unhook time = 0.6697 R^2= 67.32%

+0.0583(Pieces) **

Chokers **

-0.17201(No Chokers)

+0.03023(2 Chokers)

+0.14178(3 Chokers)

Chasers **

+0.3638(1 Chaser)

-0.3638(0 Chasers)

The combinations of the variable included the unhook equation indicate which configuration was being used based on the range of study data collected. A different model of unhook time has replaced factor variables of chokers and chasers with configuration, has a nearly equal fit. However, it may be less useful due to nesting as also highlighted with the two hook equations.

Unhook time = 0.57774 R^2= 68.54%

+0.05218(Pieces) *

Configuration **

+0.7092(North Bend)

+0.50331(North Bend Bridled)

-0.19403(Acme Shotgun)

-0.1593(Acme Slackline)

-0.34627(Falcon Shotgun)

-0.51291(Falcon Slackline)

5.4.9.2.5 Delay-Free Cycle Time

The total delay-free cycle equations developed did not include all of the variables presented in the various cycle element equations because they did not have a P-value of <0.05 and although they did affect an element time, we cannot be certain they affect the total cycle time. The total delay-free cycle time was found to be significantly influenced by the configuration, distance, piece size and number of pieces. The equation provides a reasonable explanation of the variation in cycle time considering the total number of observations (n= 253) as indicated by the R^2-value of 81.83%.

Cycle Time = 1.0349 R^2= 81.83%

+0.005013(Distance) **

+1.7536(PieceSize) **

+0.21141(Pieces) *

Configuration **

+1.8441(North Bend)

+1.8544(North Bend Bridled)

+0.336(Acme Shotgun)

+0.7644(Acme Slackline)

-2.5005(Falcon Shotgun)

-2.2960 (Falcon Slackline)

However, it's important to realize that although piece size and pieces are significant they still provide relatively little explanation of cycle time variation, most of which is explained by configuration and distance. A simplified equation containing only configuration and distance shows how much the two explain cycle time variation as indicated by the R^2-value of 79.33%.

Cycle Time = 4.4937 R^2= 79.33%

+0.005013(Distance) **

Configuration **

+2.0033(North Bend)

+2.9436(North Bend Bridled)

-0.0912(Acme Shotgun)

+0.8699(Acme Slackline)

-3.0245(Falcon Shotgun)

-2.7011 (Falcon Slackline)

Using the more complex equation for delay-free cycle time, and using the average variables observed for each configuration, we can estimate how cycle time might change with changes in distance only (Figure 5.53). Each line segment on the graph has been plotted over the range of distances which were observed for the corresponding configuration during the time study. This is not to say that each of these configurations is limited to the distances plotted, as each can be used at shorter or longer distances. The purpose of restricting the lines to the distances observed is to avoid inappropriate extrapolation of cycle times. In other words, one cannot guarantee that the cycle time does not exponentially increase or decrease after a certain distance; because cycles were not recorded at those distances.

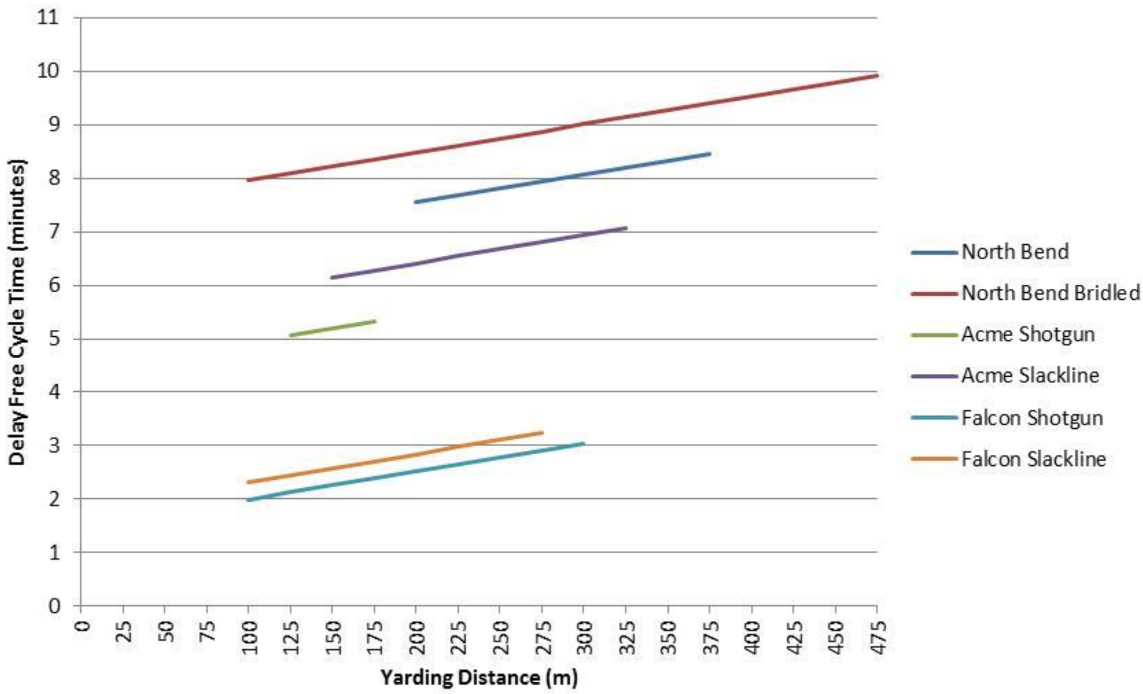


Figure 5.53: Predicted delay-free cycle time as a function of yarding distance for the six configurations studied.

5.4.9.3 Production Rate

Delay-free cycle equations are most commonly used to estimate production. The regression equation developed for delay-free cycle time was combined with the average pieces and piece size values to come up with an estimate of production based on varying distances for each configuration (Figure 5.54). It's interesting to see how North Bend, despite having a greater cycle time than Falcon Shotgun, was just as productive as Falcon Shotgun at haul distances between 200-225 meters, and becomes more productive at greater distances. These estimates of production at varying distances should still be viewed with caution as there can be considerable variability.

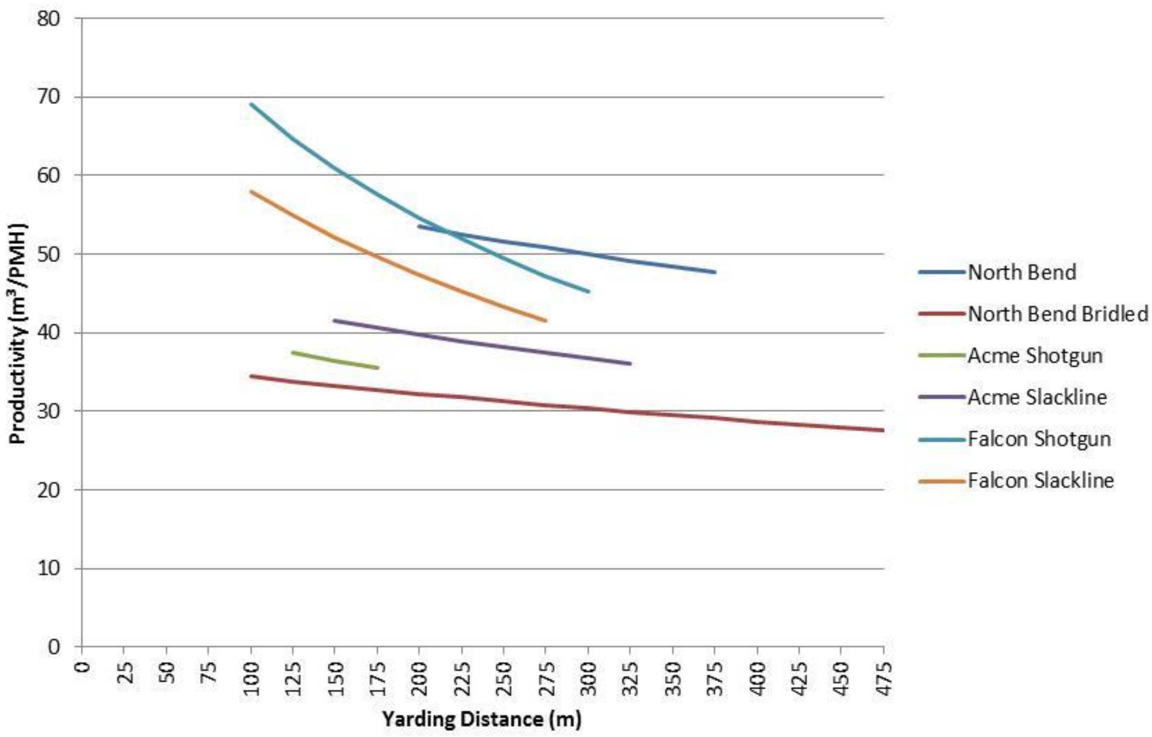


Figure 5.54: Predicted productivity (m^3/PMH) as a function of yarding distance for the six configurations studied.

The rate of production (m^3/PMH) was also calculated for each cycle based on observed data by multiplying the measured cycle volume by the number of cycles per delay-free hour. From the measured volumes and observed cycle times one can plot the range and average productivity (Figure 5.55). The highest rate of production was achieved by the Falcon shotgun configuration (46.5 m^3/PMH). However, the Falcon shotgun configuration also had the largest range in productivity and was similar to Falcon Slackline in both average productivity (44.3 m^3/PMH) and range. North Bend nearly had the highest average production rate (46.1 m^3/PMH), but also had a smaller range. Although very similar in operation to North Bend, the North Bend Bridled configuration had the lowest average production (32.8 m^3/PMH), but had a large range and was capable of higher production.

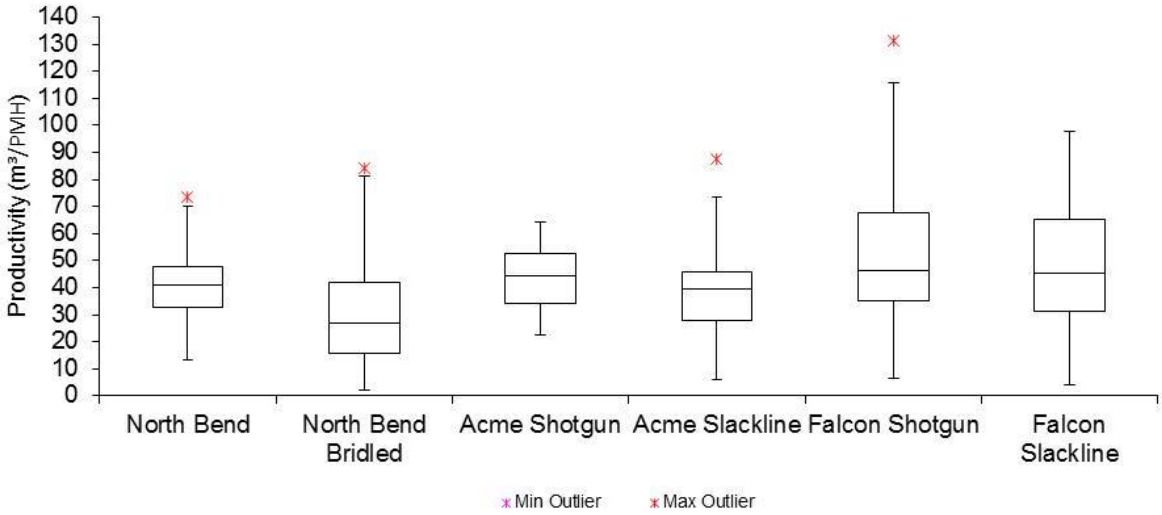


Figure 5.55: Average observed productivity (m^3/PMH) for the six configurations studied.

Some of the variability in production can be explained by the changes in distance as predicted by the increase in cycle time. However, even when distance changes little (i.e. on the cycle to cycle level) there is still considerable variability in production (Figure 5.56).

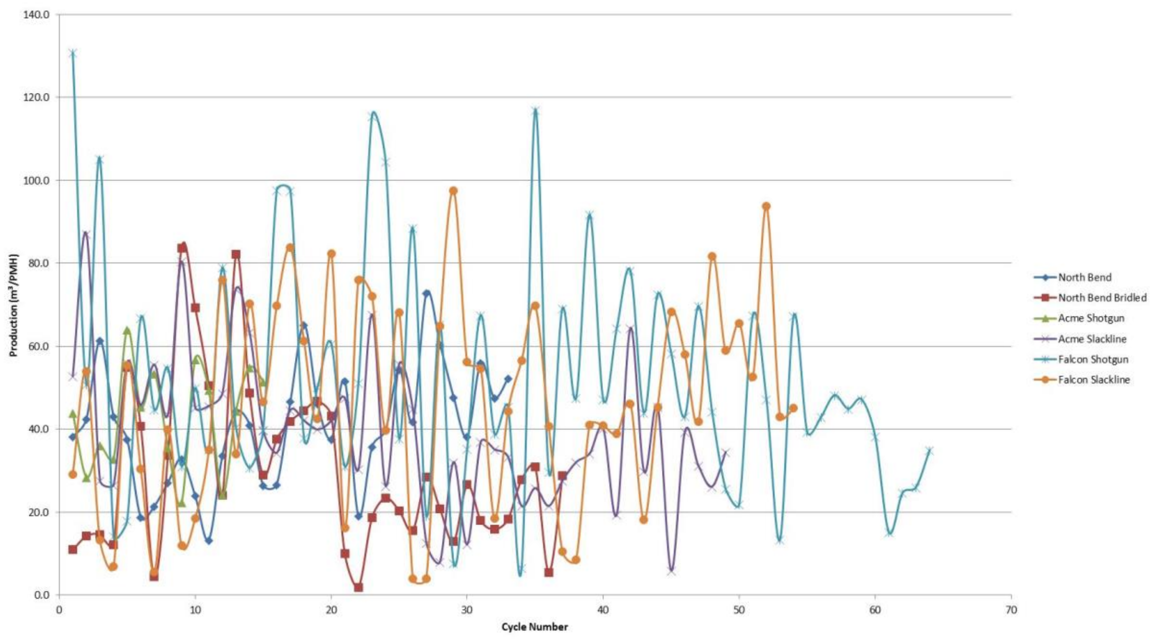


Figure 5.56: Cycle to cycle variability in productivity (m³/PMH) for each of the configurations studied.

5.4.9.4 Delay Analysis

The regression equations used to predict productivity are based on a delay-free or productive machine hour (PMH) basis, meaning they do not account for delay time. To determine what the production might be across an entire day or to estimate what costs might be, it is necessary to consider delay time. This is because labor and fixed costs are usually incurred whether or not the configuration is operated, while variable costs like fuel are. If configurations have different proportions of time they are non-operative their cost on a unit basis ($/m³) will differ as well.

Assessing the impact of delays as they relate to a specific rigging configuration is inherently complex as delay effectively occur randomly over time, and that months of data need to be collected to establish accurately figures for delays (Spinelli and Visser 2008). These time and motion studies set out to establish cycle time, and the following analyses provided is simply an indication of the delays that occurred during the study. The total delay time for all studies was 5.6 hours, relative to the total productive hours of 21.9. As such, delay factor was 0.26.

The types of delays observed for each configuration were counted to determine their frequency per cycle (Figure 5.57). The greatest frequency delay by type was due to yarder adjustments with the Acme Shotgun configuration. This is likely because of the rock bluffs encountered during the operation of this configuration, were the yarder had to adjust the length of mainline to lift the payload over the bluff, which occurred nearly every cycle. The most common delay to all other configurations was due to repositioning the carriage, especially for the Falcon shotgun, Falcon Slackline and North Bend Bridled configurations. The grapple carriages experience this delay because they have either lost a log out of the grapple and have to pick it up, or because first placement of the carriage after outhaul is not adequate to pick up “grapple” the log. The North Bend Bridled configuration experiences a repositioning delay because after the carriage stops moving the fall block has to drop and move laterally; sometimes it is difficult to land the rigging this way and the choker-setters have to communicate with the yarder operator to land the rigging. There were also a number of delays associated with the landing itself. Like waiting for the loader to clear the chute (an interaction delay between machines), and difficulty landing logs which was usually due to the logs not resting properly on the landing (inadequate space) or tangled chokers.

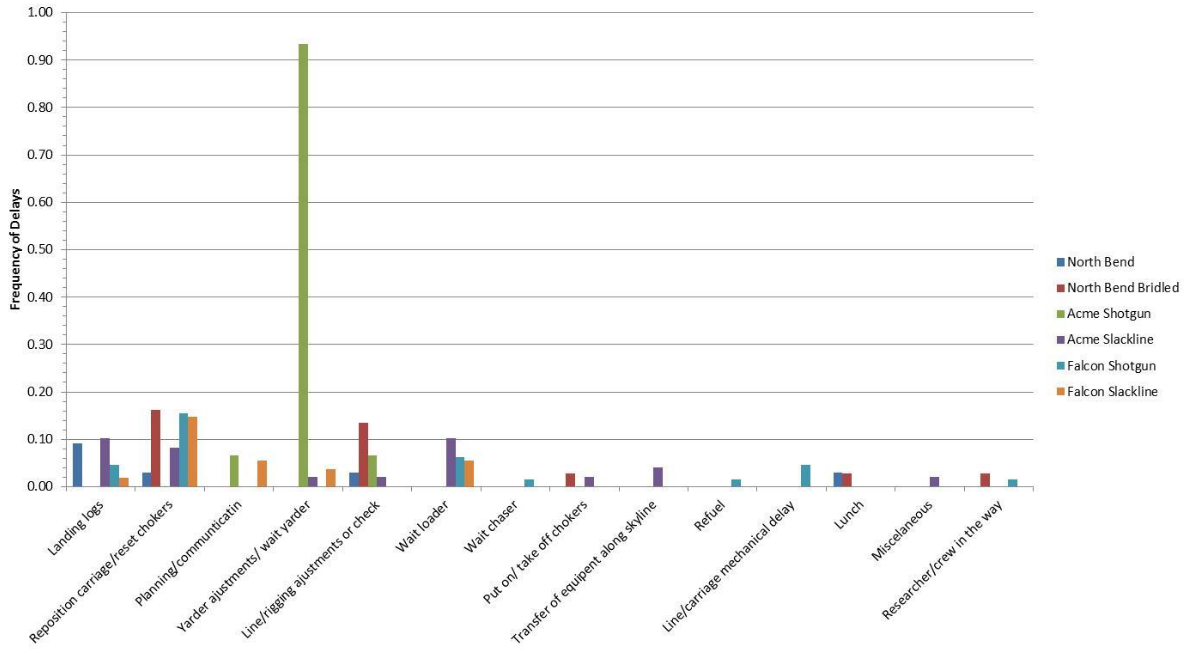


Figure 5.57: Frequency of observed delays by type for the six configurations studied.

The average delay time for each category observed for each configuration was also calculated to determine which type of delays were consuming the most productive time (Figure 5.58). Although, some delays like yarder adjustments with the Acme Shotgun configuration were frequent they account for very little time on average (0.02 minutes). On the other hand infrequent delays like line and rigging adjustments or lunch, can account for a relatively large average delay time (>10 minutes) and (>30 minutes) respectively. The most time consuming delay that was most frequent was the reposition carriage delay associated with the North Bend Bridled configuration. As previously mentioned this delay occurred often due to the nature of operation, but also because of its difficulty, takes on average 2.4 minutes.

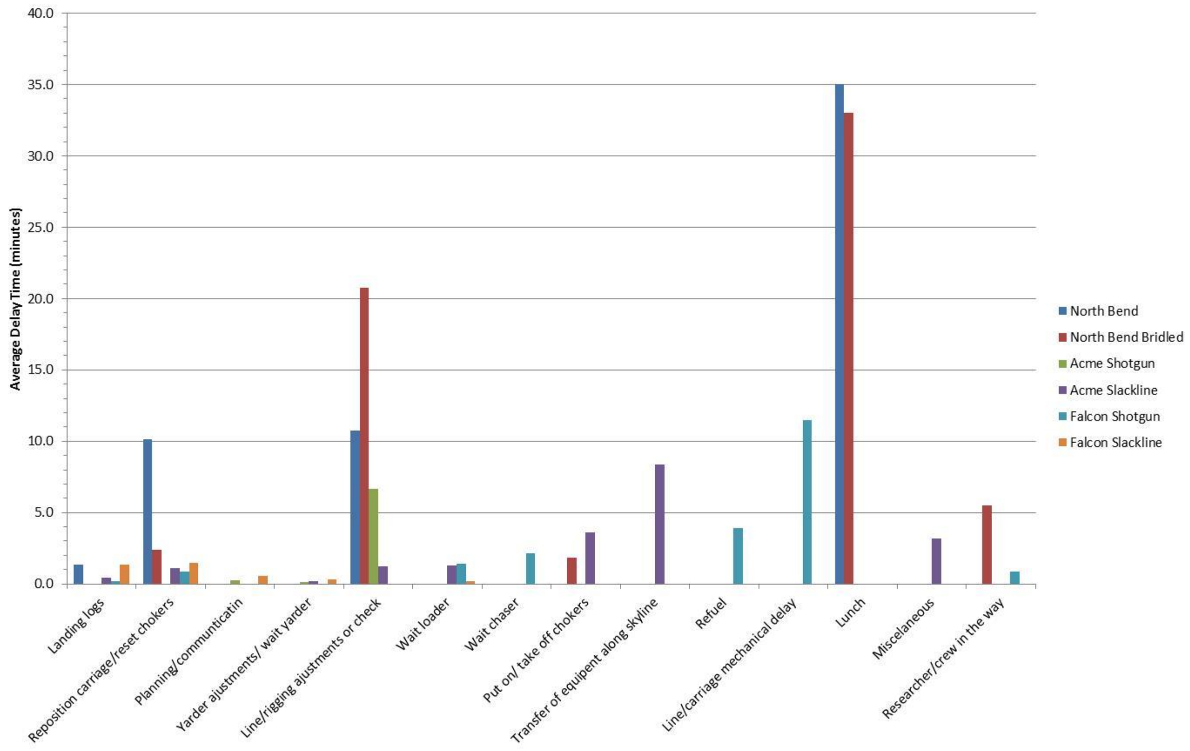


Figure 5.58: Average delay time (minutes) categorized by each type of delay for the six configurations studied.

The delays recorded during time study are a good indication of delays that might be expected when operating each of the configurations studied. They should be used with caution as some delays as previously discussed (e.g. Acme Shotgun yarder adjustments) were very specific to unique site conditions encountered. Additionally, not every operation was studied for the same time period, or same range of operating hours (i.e. half day vs full day). An attempt was made to normalize delay times by excluding infrequent large delays, research related delays and delays that have common times to all configurations but were not captured during the time study (e.g. lunch & line shifts). Utilization rate was calculated for each configuration by using the productive time as a ratio of total time (sum of delays and productive time), and presented in both observed and adjusted (normalized) ratios (Table 5.13). The highest utilization was achieved by the Falcon Slackline configuration while the lowest was achieved by the North Bend Bridled configuration. It is interesting to notice that the adjusted utilization rates are similar between variations of configurations with exception to North Bend and North Bend Bridled. This is most likely due to the high frequency (0.13) of line/rigging adjustment delays (off-setting haul back blocks), and the average time for this type of delay (>20 minutes); which were not observed with the North Bend configuration.

Table 5.13: Productive time, delay times adjusted and non-adjusted and corresponding utilization rate (%) for each configuration studied.

	North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Productive Time (min)	264	331	76	321	165	158
Delay Time (min)	60	158	9	38	56	16
Adjusted Delay Time (min)	25	120	9	35	27	16
Utilization Rate (%)	81	68	89	89	75	91
Adjusted Utilization Rate (%)	91	73	89	90	86	91

5.4.9.5 Labor and Energy Consumption

Each configuration as previously discussed had a different average production rate (m^3/PMH), but productivity alone does not tell us how profitable these configurations are. For example, each configuration has different requirements of labor (number of workers), and can be used on a variety of different yarders with different fuel consumption rates. Unless one knows the proportion of costs associated with fixed, variable and labor in detail, on a productive machine hour basis, cost competitiveness cannot be compared. Collecting detailed cost data was not within the scope of this study. However, even these costs are known, cost competitiveness can be compared through the rates of consumption of labor (man hours/m^3) and energy from the yarder and carriage combination (kW/m^3). In addition, rates of labor and energy consumption provide insight to the relative amount of effort expended to produce a m^3

on an hourly basis (Table 5.14). The consumption of labor was computed by dividing the number of workers (sum of choker-setters and chasers + yarder operator) by the production rate (m^3/PMH). The consumption of energy was computed by dividing the sum of the carriage and yarder kW by the production rate (m^3/PMH).

The data obtained from these eight sites do not represent a full factorial study of rigging configuration, labor and yarder engine power. As such the data presented in this section should only be interpreted as case study based. The lowest rate of labor consumption was achieved by the Falcon Shotgun configuration which is similar to Falcon Slackline, as these configurations use a grapple carriage and only require a yarder operator and one additional worker to move the anchor machine. The highest rate of labor consumption was achieved by the North Bend Bridled configuration, which used four or sometimes five workers. The difference in labor consumption between North Bend and North Bend Bridled even though they use the same amount of workers is attributable to the increased production of North Bend. A similar but not as extreme trend is found between the Acme carriage configurations and the Falcon carriage configurations, where the Shotgun variation has a higher rate of production. The Acme carriage configurations fall between North Bend and either Falcon configurations' in terms of labor consumption due to higher production than North Bend with the same amount of workers.

Table 5.14: Average and range of labor and energy consumption for each configuration studied.

Consumption Rate		North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Labor	Min	0.04	0.05	0.05	0.05	0.02	0.02
(man hours/m³)	Max	0.57	2.06	0.14	0.84	0.87	0.50
	Avg	0.12	0.29	0.08	0.13	0.07	0.09
Energy	Min	4	4	4	4	3	4
(kW/m³)	Max	38	172	11	98	164	95
	Avg	9	25	7	11	15	17

Energy consumption was lowest with the Acme Shotgun configuration followed closely by North Bend. This is because they require relatively low total kW's and achieve a relatively high rate of production. The highest rate of energy consumption was through the use of the North Bend Bridled configuration. Despite not having a powered carriage North Bend Bridled's low production rate overrides its power savings. It's interesting to note how despite having a high production rate and the same yarder kW's as other configurations, the Falcon configurations have relatively high energy consumption due to the increased total kW's from the carriage (15-17 kW/m³). There is also a similar trend as observed with labor consumption where the Shotgun variation of the Acme and Falcon configurations consume less energy, which again can be contributed to the higher associated rate of production.

5.4.10 Skyline Tension Analysis

5.4.10.1 Configuration and Element Tensions

The tension monitoring results for each cycle of each configuration at every study site were summarized to compare the maximum and average tensions for the configurations studied.

5.4.10.2 Maximum Tensions

Results show the highest average of maximum skyline tensions measured were associated with the North Bend Bridled, Acme Slackline and Falcon Shotgun configurations, respectively (Figure 5.59). The average of these peak tensions was higher than the other configurations, most likely due to the profiles which had minimal deflection and or long skyline spans. North Bend Bridled showed high average maximum tensions in all elements of the cycle due to the effect of off-setting the haulback blocks, which contributes to an extra plane of force in the skyline. While the live skyline systems such as Falcon Shotgun and Falcon Slackline have higher outhaul and hook tensions compared to standing skyline system alternatives like Acme Shotgun and Acme Slackline. North Bend performed quite well compared to others with relatively low tensions in all elements of the cycle except for inhaul.

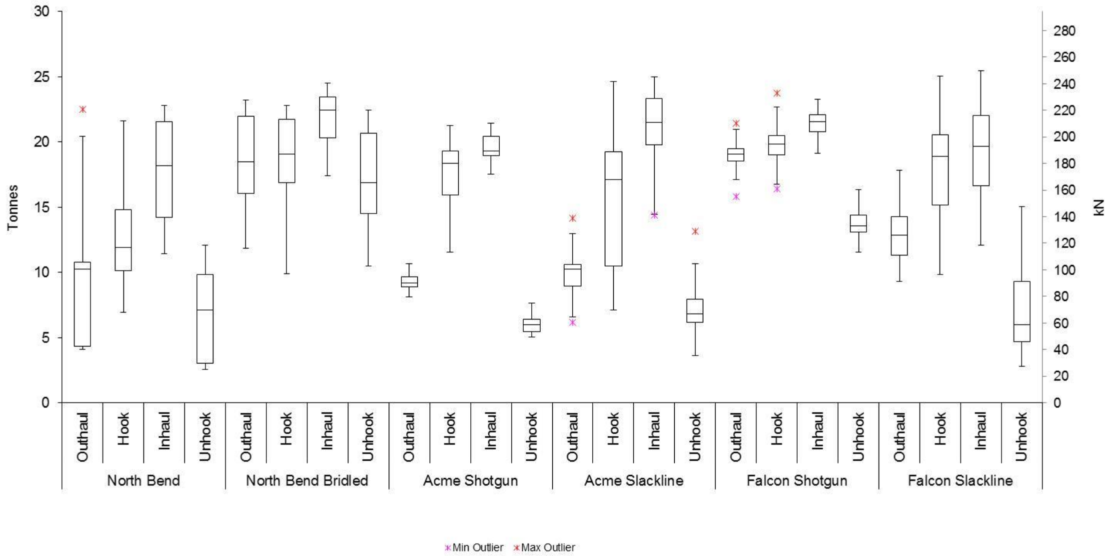


Figure 5.59: Peak skyline tensions recorded by yarding cycle element for all cycles of each configuration studied.

5.4.10.3 Average Cycle Tensions

Results have shown the maximum tensions, but knowing that these peaks may only occur for a small portion of the total cycle time, it may benefit to investigate what the average cycle tension was. Skyline tensions recorded 10 Hz were averaged for each cycle for each configuration and converted to a percent of the skyline safe working load for comparison between configurations (Figure 5.60). North Bend Bridled had the greatest average tension per cycle operating at 81% of the safe working load, followed by Falcon shotgun which operated at 63% of the safe working load per cycle. The inconsistent element times and associated tensions compounded by more than one site worth of data produced greater variability in average tension per cycle for North Bend and North Bend Bridled, and to a lesser extent Acme Slackline.

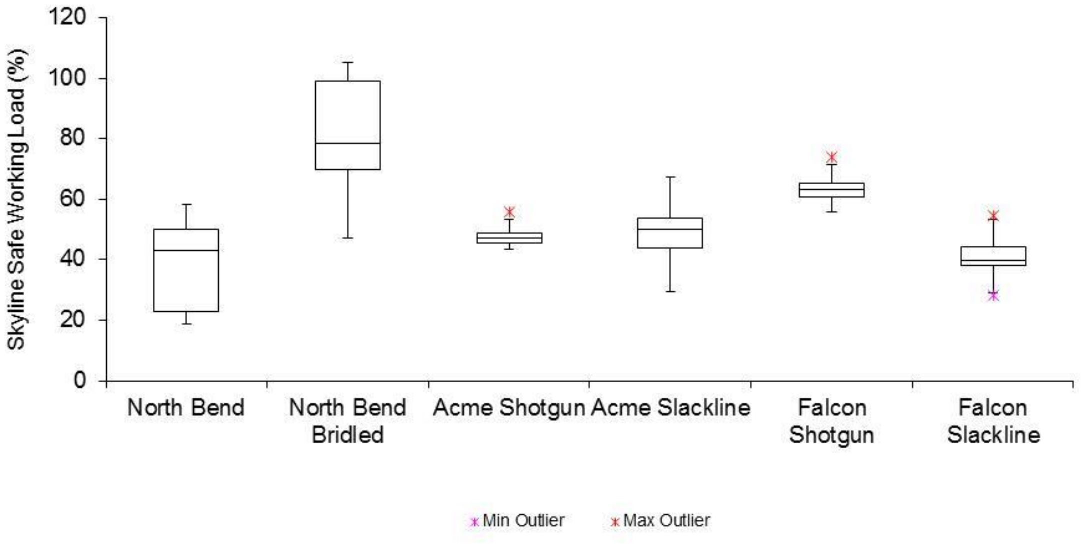


Figure 5.60: Average percent of the skyline safe working load per cycle for all cycles of the configurations studied.

5.4.10.4 Regression Model for Tension

In order to determine conditions are affecting tension of each configuration, regression analysis was performed using the measured variables from each cycle. The range of these values recorded during the time study and there averages were summarized (Table 5.15).

Table 5.15: Summary of representative values of the variables recorded for each configuration during the study.

Independent Variables		North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Span (m)	Min	395	920	354	284	338	345
	Max	940	1100	354	335	602	364
	Average	602.3	1076.9	354.0	308.8	480.8	353.3
Chord Slope (%)	Min	-14	-43	-23	-21	-47	-27
	Max	1	-14	-23	-17	-30	-26
	Average	-4.9	-39.3	-23.0	-19.4	-37.9	-26.7
Deflection (%)	Min	5.2	3.8	6.2	4.2	5.7	5.9
	Max	10.05	5.1	6.2	6.9	6.05	7.4
	Average	7.8	4.0	6.2	6.1	5.9	6.3
Pieces (#/cycle)	Min	2	1	1	1	1	1
	Max	6	4	3	11	3	4
	Average	4.2	1.9	2.1	2.4	1.5	1.4
Carriage Payload (tonnes)	Min	3.9	1.3	3.2	1.5	2.5	2.4
	Max	10.3	11.5	5.9	10.0	6.6	8.0
	Average	6.9	5.9	4.4	5.2	4.3	4.4
Piece Size (m^3)	Min	1.2	2.4	1.5	1.5	1.4	1.6
	Max	2.4	2.4	1.5	2.1	2.4	1.6
	Average	1.6	2.4	1.5	1.8	1.5	1.6
Yarding Corridors		2	2	3	2	2	3
Cycles		23	34	42	27	34	54

Variables are only included in the equation if their associated coefficient is significantly different from zero at an acceptable probability level. In this study variables were only included in the final predictive equation if their P-value was less than 0.01 (**) or less between 0.05 and 0.01 (*). Regression equations also have an R^2 value known as the multiple correlation coefficient, which is a measure of fit between the observed time and the equations calculated time. An R^2 value of 100% indicates a perfect fit between the observed and predicted tension. The equation, R^2 value and the level of significance of each variable included in the model were calculated:

Avg. Skyline Tension (tons) = 12.538 $R^2 = 78.05\%$

-1.1721(Deflection) **

+0.00863(Span) **

+0.22509(Carriage Payload) **

Configuration **

-1.36810(North Bend)

-1.2967(North Bend Bridled)

-0.4906(Acme Shotgun)

+0.9471(Acme Slackline)

+2.6463(Falcon Shotgun)

-0.4380(Falcon Slackline)

All variables included in the final equation were statistically significant (P-value <0.01). Deflection was found to have the greatest influence of all independent variables on average cycle tension followed by carriage payload and span. A one-way ANOVA test indicated that configuration alone was statistically significant (p-value <0.01) and the configuration alone explained nearly half of the variation in tensions ($R^2 = 54\%$). The ANOVA test also showed that North Bend Bridled and Falcon Shotgun were significantly different than all other configurations. While, there was no significant difference between Acme Shotgun, Acme Slackline and North Bend. Additionally, there was no significant difference between Acme Shotgun, North Bend and Falcon Slackline. However, these two groups of three configurations were significantly different from one another despite have commonality with the North Bend configuration.

Using the above general linear model equation for skyline tension (tons), and using the average variables observed for each configuration, we can estimate how average tension might change with changes in deflection only (Figure 5.61). Each line segment on the graph has been plotted over the range of deflections which were observed for the corresponding configuration during the time study. This is not to say that each of these configurations is limited to the deflection plotted, as each can be used at greater or lesser deflection. The purpose of restricting the lines to the distances observed is to avoid inappropriate extrapolation of average tension. The equation after all is only applicable to the conditions studied, and much more thorough equations exist, which indicate that there is not a linear relationship between tension and deflection.

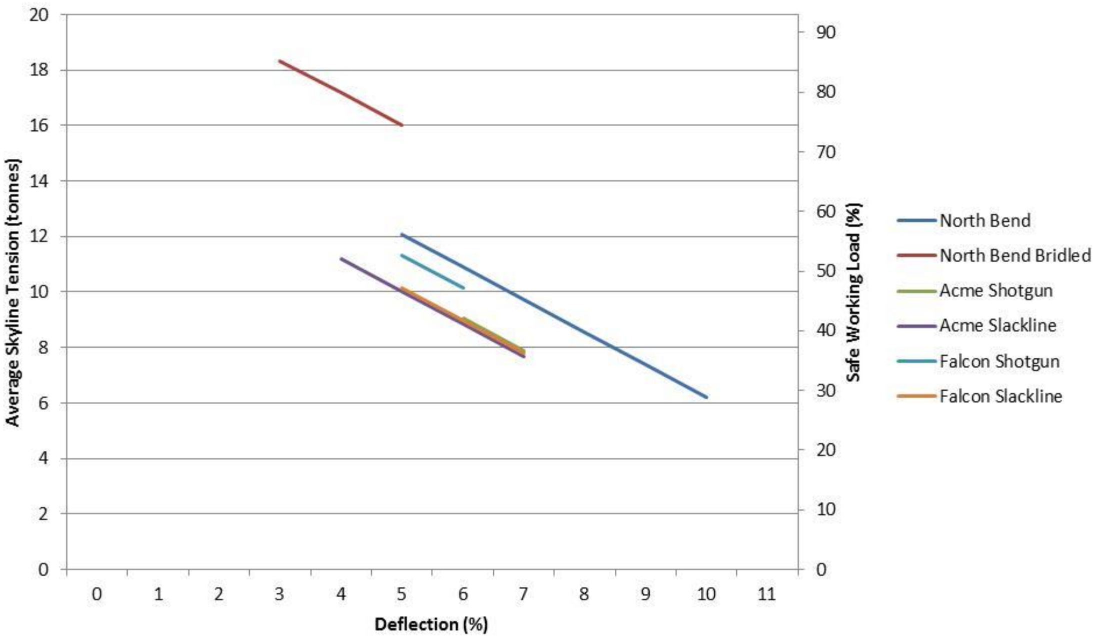


Figure 5.61: Predicted average cycle skyline tension for each configuration studied.

5.4.10.5 Payload to Tension Relationships

One of the objectives of this study was to investigate the carriage payload (sum log and carriage weight) to tension relationship for each configuration. Deflection as previously discussed, has a significant influence on tension, the varying ranges of deflection were categorized into classes (<5% = minimal, 5-7% = low, 7-10% = medium, >10% high) for ease of plotting the carriage payload to tension relationship for each configuration (Figure 5.62). The scatter plot of data shows that reduced deflection increases the skyline tension during inhaul, for an equivalent carriage payload. The shows the variability in tension for similar payloads when using the Falcon Shotgun and Falcon Slackline configurations indicated by empty and solid circles. However, the variability in tensions for the grapple carriage configurations are not well explained by the deflection, due to the nature of operating this type of live skyline system; where the carriage height and therefore deflection are altered during each cycle. The variation in carriage height for the Falcon Shotgun configuration compared to North Bend was shown in the carriage GPS positional data acquired (Figure 5.63;Figure 5.64). Therefore, the deflection estimates for the grapple carriage configurations are imperfect, and only represent the maximum allowable deflection measured for each profile studied.

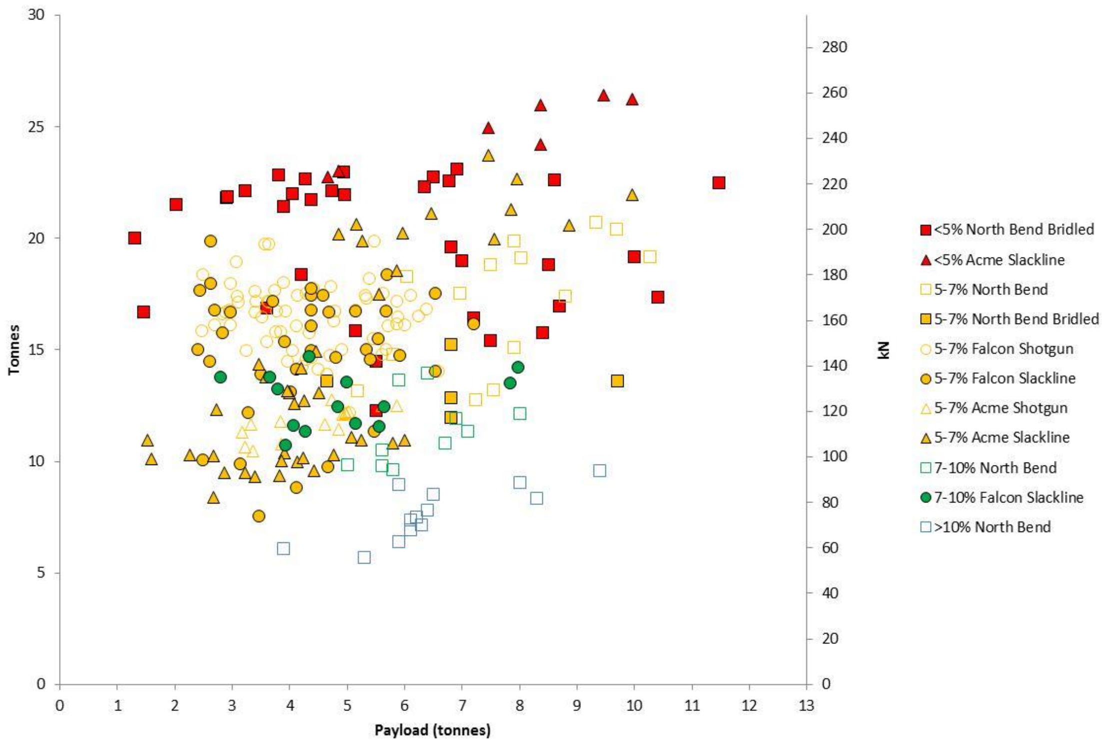


Figure 5.62: Payload to average skyline tension during inhaul relationship by percent deflection for all configurations studied.

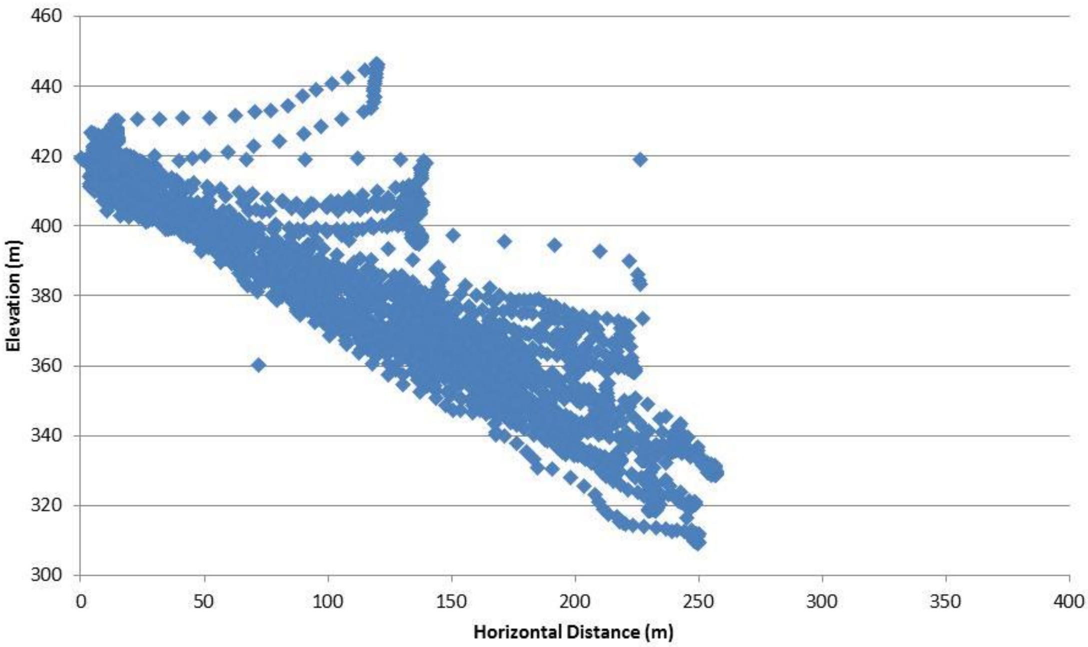


Figure 5.63: Carriage mounted GPS positional data for study site five, profile one, Falcon Shotgun configuration.

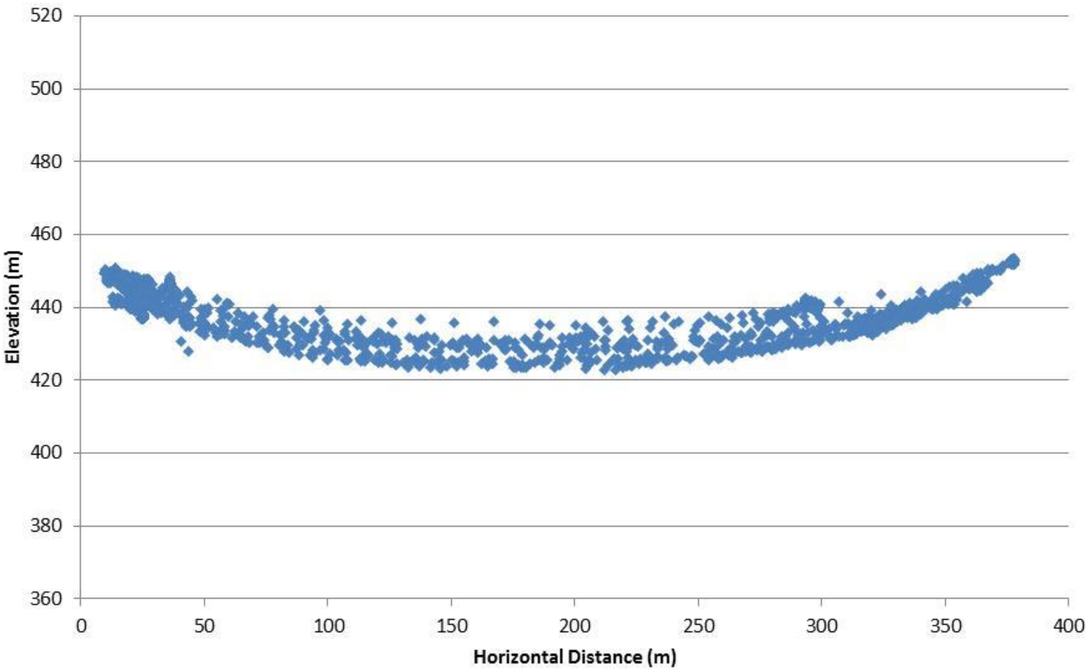


Figure 5.64: Carriage mounted GPS positional data for study site seven, profile two, North Bend configuration.

Another interesting trend in the payload to tension relationship was the high tensions generated for low carriage payload when the North Bend Bridled configuration was used, compared to the very similar North Bend configuration (Figure 5.65). For example, in the North Bend Bridled configuration operated at minimal deflection (<5 %) equally high tensions were recorded during inhaul for a four and an eight tonne carriage payload. The same flat relationship between payload and tension indicated by the trend lines in Figure 5.65 was observed for North Bend Bridled was operated at low deflection (5-7 %). While, the data shows that the same increase in payload (four tons) for the North Bend configuration results in a tension increase of nearly five tons; a positive relationship shown by the trend lines. The resulting high tensions are likely a result of the added plane of force in the skyline when the haulback blocks are off-set from the skyline as previously discussed.

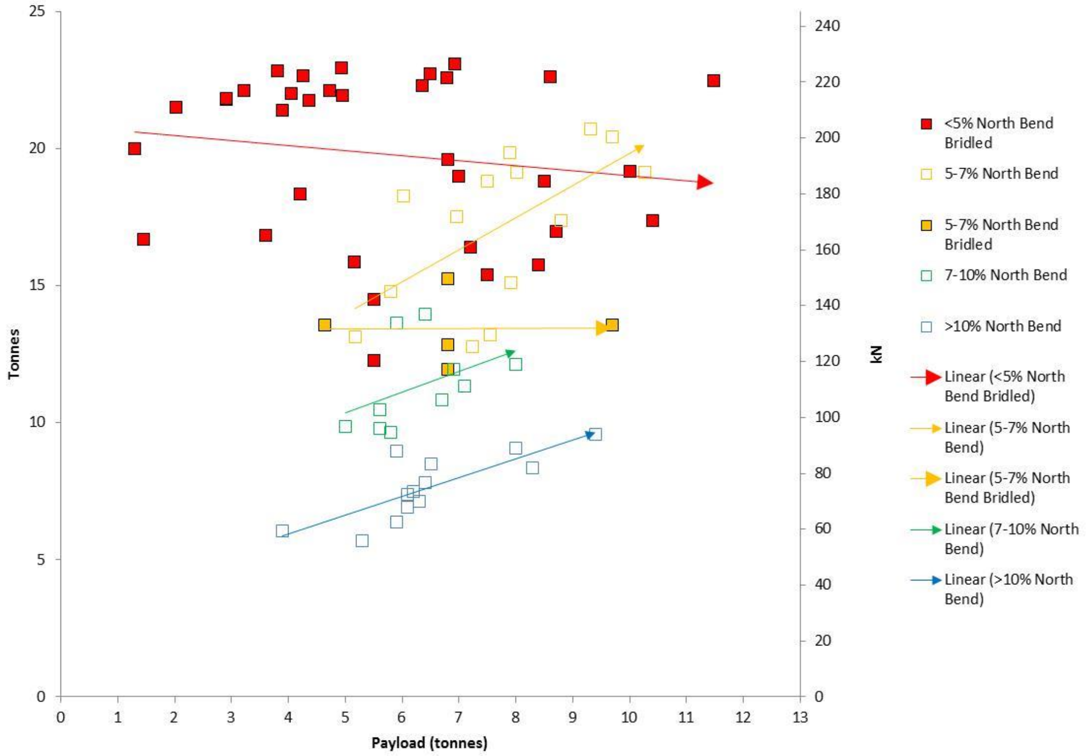


Figure 5.65: Trend in payload to average skyline tension during inhaul relationship by percent deflection for North Bend and North Bend Bridled configurations.

5.4.10.6 Skyline Dynamic Behavior

5.4.10.6.1 Amplifications

Another objective of the study was to investigate dynamic load behavior referred to as shock loading, and compare these dynamic load behaviors between rigging configurations. (Pyles et al. 1994) said that dynamic load magnitude was possibly the most valuable parameter that tension monitoring of logging cables could produce. The two types of dynamic loads amplifications calculated from tension monitoring results were the breakout tension factor and the maximum cyclic load factor (Figure 5.66). The breakout tension factor is the amplification of skyline pretension expressed as a factor of the skyline pretension; or how much tension is generated in the skyline to get the load to start moving. The maximum cyclic load amplitude factor is defined as the greatest peak to peak change in tension during inhaul, expressed as a percent of the skyline pretension.

Results show that the breakout tension factor was lowest for the North Bend and North Bend Bridled configurations; where little tension in the skyline is needed to start the load moving due to the fall block creating a purchase in the mainline, and the extra plane of force when Bridling. However, breakouts at mid-span even with high deflection (> 10%) can produce a large breakout factor. The breakout tension factor was highest for the Falcon Slackline and Falcon Shotgun configurations; where the skyline was purposely tensioned to facilitate breakout of the load. It's interesting to note how despite similar spans, a lower average safe working load per cycle and lower average peak tensions for each element of cycles, Falcon Slackline had more than twice the breakout tension factor of Falcon Shotgun. The difference in amplification factors between the two grapple carriage configurations can be attributed to the style of operation previously described; where at study site one when the Falcon Slackline configuration was operated the carriage was raised to facilitate inhaul directly to the landing versus mirroring the slope during inhaul and performing several smaller lifts along the way. The maximum cyclic load factor was greatest for the falcon slackline configuration; due to the high tensions during inhaul and occasional load contact with the ground especially as it approached the landing. Contact with the ground showed increased cyclic load factors as highlighted by the comparison between Acme Slackline in the 4.2 % deflection profile and the 6.1% deflection profile where the operator purposely kept the logs in contact with the ground. The lowest cyclic load factors were observed during the use of the North Bend Bridled configurations; as previously discussed there was somewhat of a damping effect to the skyline with the extra plane of force from off-setting the haulback blocks.

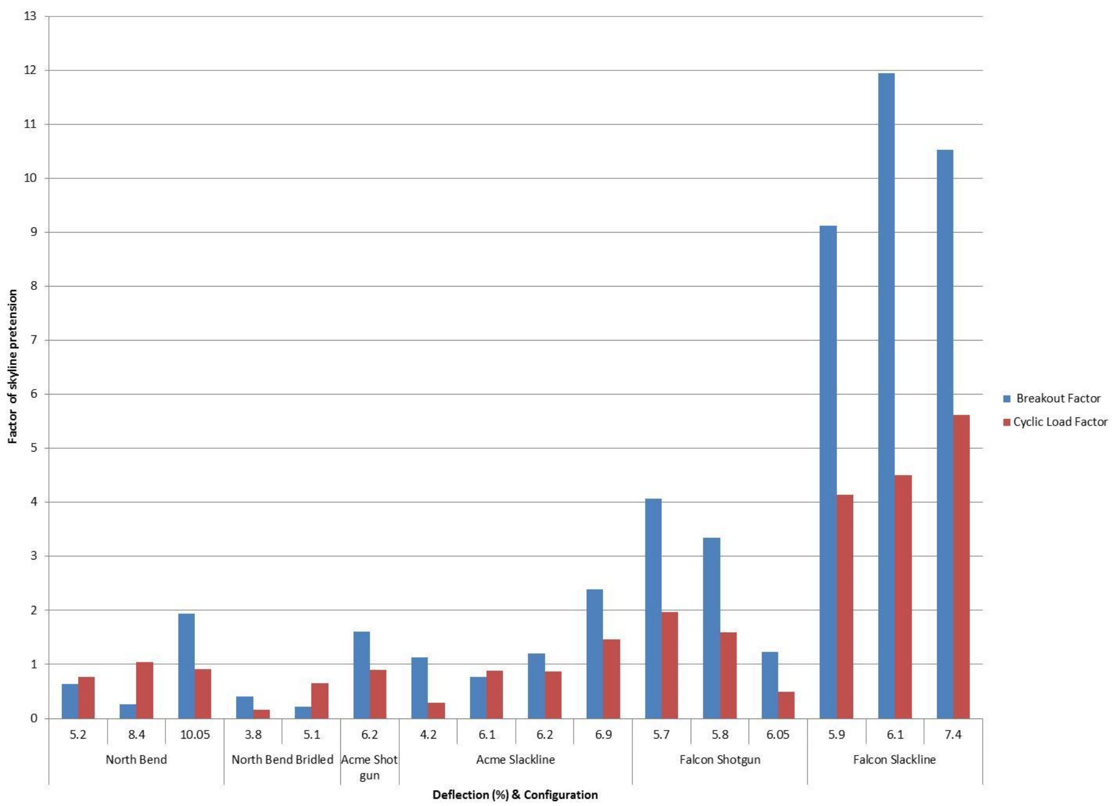


Figure 5.66: Dynamic skyline load magnitude averages for various rigging configurations and their corresponding span deflection (%).

5.4.10.6.2 <u>Hang-Up During Breakout</u>

Hang-ups or collisions with ground object can cause large dynamic skyline load magnitudes. As previously discussed in the results of study site seven, there were two different profiles with 8.4 and 10.1% deflection respectively. However, the first cycles of the 10.1% deflection span were extracted from an incised gulley at mid-span, whereas all of the cycles in the other profile were extracted from the back face. Cycle number 13 from this span had a hang-up during breakout where the butt ends of one or more stems were lodged into the lip of the gulley. The payload of logs in the cycle was approximately five tones but generated a peak tension of over 20 tons (196 kN) which was greater than all other cycles form that profile (Figure 5.67). Cycle 13 had a breakout factor of 4.5 compared to all other cycles from that span which had a maximum breakout factor of 2.3. Cycles from the two profiles had similar average cyclic load factors 1.04 and 0.92, respectively; but very different breakout factors (0.26 and 1.95), due to the later extracting loads near mid-span.

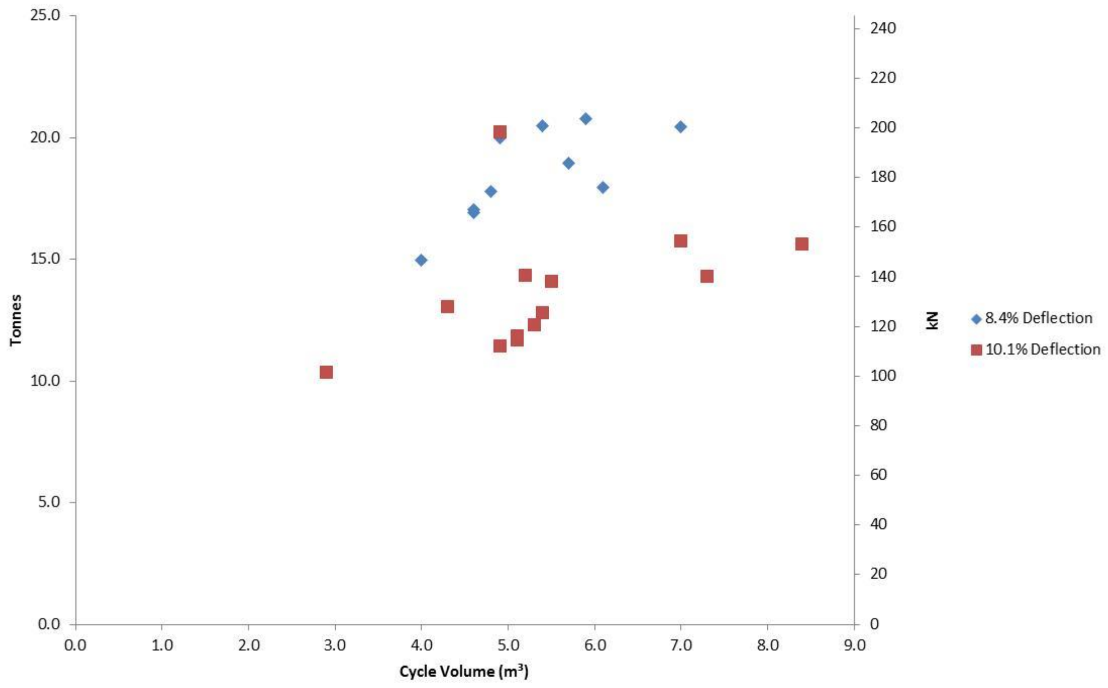


Figure 5.67: Peak tensions during inhaul based on cycle volume for study site seven, profiles one and two, North Bend configuration.

5.4.10.6.3 Partial or Full Suspension

During inhaul payloads can either be partially suspended or fully suspended. Partial suspension shares the weight of the load with the ground so in theory there is less tension in the skyline at a given deflection. However, partially suspending loads means they are also more subject to shock loads due to hang-ups with objects, and to a lesser extent the resistance due to the coefficient of friction with the ground. As previously discussed in the results from study site four, profile two, where the Acme Slackline configuration was operated; stems were partially suspended form the back face of the canyon. The operator stated that he knew high tensions were occurring during inhaul because his tension monitor in the cab would ring an alarm when the safe working load was exceeded. He was concerned that fully suspending loads from the back face was a potential hazard. The effect of partial versus full suspension on skyline behavior can be fairly compared by the inhaul of cycle 16 and 17 (Figure 5.68). In cycle 17 the operator was advised to fully suspend one stem rather than partially suspending two stems across the canyon. The payload was reduced from 4.7 to 3.6 tons, but the inhaul time reduced from 3.5 to 2.0 minutes, which resulted in an increase of more than 10 tons/PMH. Even though the peak tensions were similar during inhaul of cycle 16 and 17, the maximum cyclic load amplification was reduced from 1.5 and 0.68.

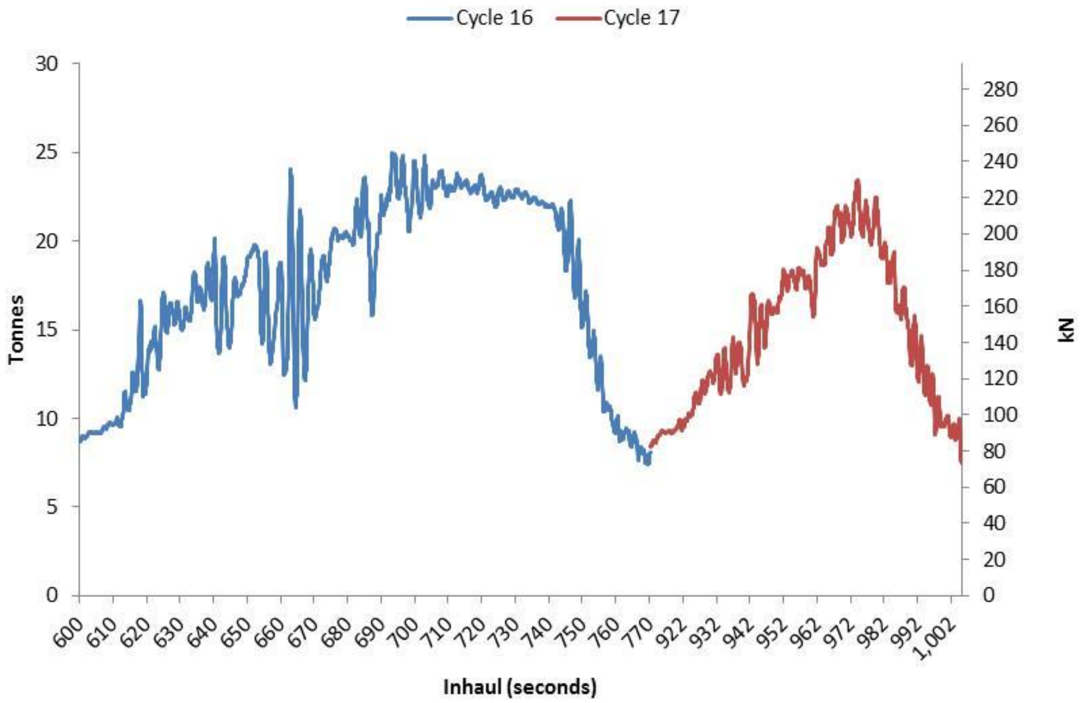


Figure 5.68: Comparison between inhaul tensions of cycle 16 and 17, study site four, profile 2, Acme Slackline configuration.

5.4.10.6.4 Cyclic load Frequency

During the monitoring of skyline tensions across a total of 259 cycles, the tension monitor was knocked off the skyline where it was clamped on two occasions as previously discussed in the results from study site two and six. Further investigation into these events found that they were a result of high tensions during inhaul and outhaul. In the case of study site six the safe working load was exceeded on 22 out of 33 cycles during inhaul. On one occasion during inhaul the skyline drum's band brake slipped at 27 tons (265 kN) which was 127% of the safe working load (42% breaking strength) nearly reaching the endurance limit (50% breaking strength); indicating that the band brake was not calibrated or functioning correctly. The event caused several wraps of cable to come off the drum all at once. The result was a large shock load wave which travelled down the skyline to the tailhold which slammed the tension monitor into the ground, knocking it loose from the skyline. In the case of study site two the carriage was outhauled to extract stems 25 meters in front of the anchor. Due to the steep chord slope (47%) and carriage weight (2.2 tons) the carriage was able to outhaul at an extreme speed (15m/sec) and the peak skyline tension (21.2 tons, 209 kN) nearly reached the safe working load. The tension monitor did not make impact with the ground like study site six, but was still disconnected from the skyline. The video analysis showed the tension monitor begin to shake violently as the carriage approached the anchor. Further investigation revealed that the maximum cyclic load factor (1.6) was similar to other cycles, but the frequency of cyclic load peaks were not (Figure 5.69). Results show that although peak tensions were similar pre and post 1,155 seconds the frequency nearly doubled from 1.6 to 3.5 Hz. Measuring the natural frequency was not within the scope of this study but, it's possible that the carriage could have exited the natural frequency causing a resonance effect as suggested by Pyles and others (1994). Perhaps of greater concern, would be the potential wear on the skyline where it passes over sheaves or is shackled, with this high frequency behavior at high outhaul tensions. Carson and Jorgensen (1978) highlighted that this behavior could induce wear to the skyline due to stress reversal fatigue, and that higher average frequencies reduced skyline life.

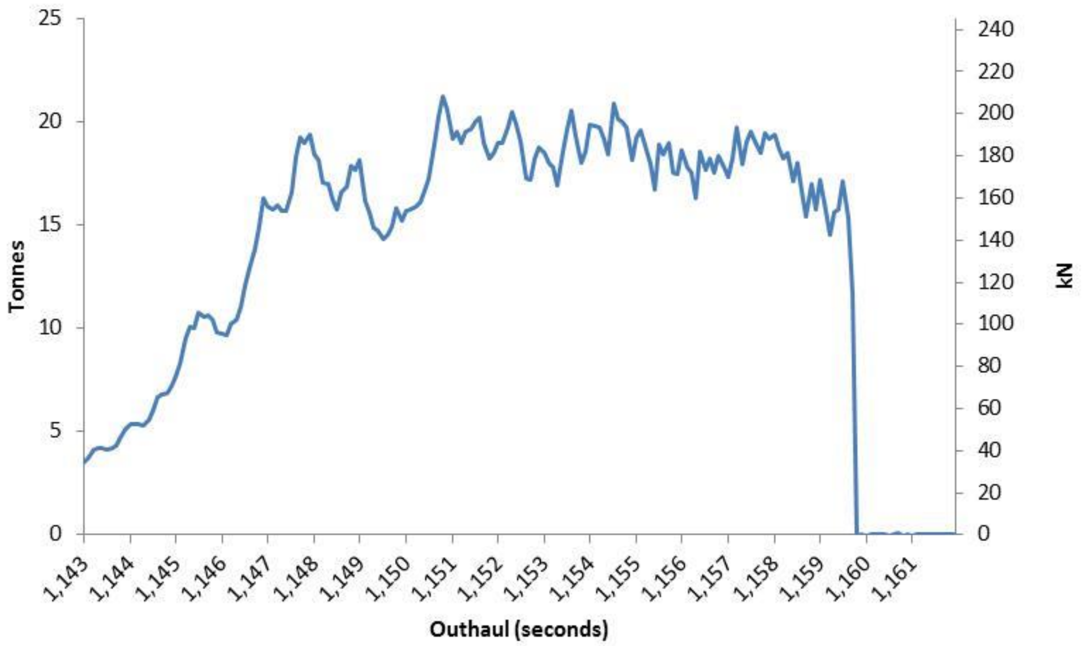


Figure 5.69: Outhaul tensions for study site two, profile one, cycle 16, Falcon Shotgun configuration.

5.4.10.6.5 *<u>Payload & Tension Efficiency</u>*

Measurements of efficiency can provide insight into the performance of any operation. Two measures of efficiency were calculated for each rigging configuration; payload efficiency and tension efficiency (Figure 5.70). The payload efficiency is the measure of how close an individual cycle payload was to the predicted payload from payload analysis software at the same extraction distance. Tension efficiency is the measure of how close the average tension of a cycle was to the safe working load of the skyline. Through comparing these measures side-by-side we can determine whether the payloads or tensions were limiting the configuration from achieving higher production. Results show the greatest payload efficiencies were achievable through the use of North Bend and North Bend Bridled. However, these measures are inflated due to payload analysis software predicting low payloads where achievable. This is a known issue as current payload software does not have a dedicated algorithm for the North Bend and North Bend Bridled configurations; they are analyzed using the standing skyline procedure (Woodruff 1984). Although they are technically a standing skyline system, the fall block and terminal functions of the mainline and haulback differ. For example the North Bend Bridled operation at study site six had minimal deflection and a blind lead area where little log suspension could be generated; the payload analysis software indicated no stems could be yarded form this area. However, the mainline and haulback were able to pull the loads along the ground at this point similar to the configuration Highlead, and production continued. Payload efficiency may never reach a factor of one for many configurations and setups, as yarder mechanics may limit their capability to lift and transport the load (Wilbanks 1985). Additionally, peak skyline tensions may deter one from maximizing payload. The more concerning trend is when payload efficiency is less than tension efficiency; which indicates that higher payloads could be achieved. The Falcon Shotgun configuration at study site two and five show a payload efficiency was less than tension efficiency because only 1.5 and 1.4 stems were grappled on average resulting in a payload efficiency of 0.30 and 0.39, respectively; compared to when two stems were grappled 0.53 and 0.47 respectively. It’s interesting to note how the Falcon Slackline configuration had the opposite trend between payload and tension efficiency due to the difference in operating style as previously discussed; even though payload efficiency was above a factor of one tension efficiency was less than 0.50. Additionally, the operating style of the Acme Slackline configuration at study site four where the operator was trying to partially suspend the loads showed this technique maximized the payload efficiency while it had a relatively low tension efficiency despite exceeding the safe working load briefly nearly every cycle.

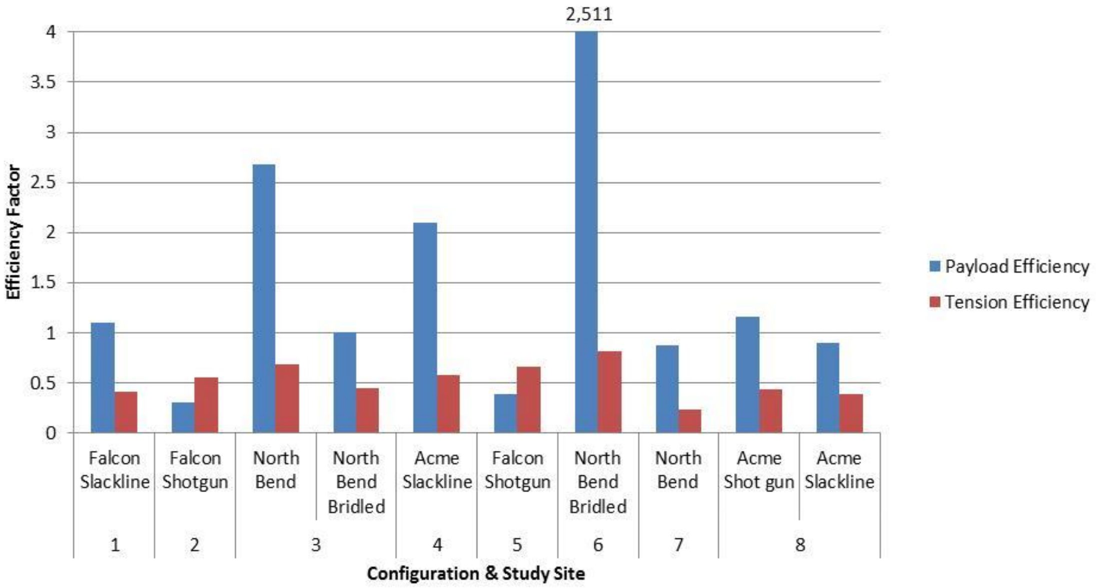


Figure 5.70: Average payload and tension efficiency for each configuration and study site observed.

5.5 Conclusion

This study was conducted to compare the operational characteristics of rigging configurations used in New Zealand. Based on previous literature and studies, the most commonly used configuration (North Bend/North Bend Bridled) was studied along with other configurations popular and newly developed configurations (Acme Shotgun/Slackline and Falcon Shotgun/Slackline). These configurations differ in delay free cycle times, productivity, incurred delays, and with their rates of labor and energy consumption. These differences mainly exist between unique configurations but can also differ within slight variations of the configurations.

Regression equations were developed to predict delay-free cycle times, which showed that cycle time increased with increased distance but was also significantly affected by the configuration used. The largest predicted cycle times were associated with the North Bend Bridled configuration, while the shortest were predicted for the Falcon Shotgun Configuration. The Acme Shotgun and Falcon Shotgun configurations were shown to have faster cycle times compared to the Acme Slackline and Falcon Slackline configurations due to their speed of gravity outhaul. Hook time was faster with the Falcon carriage configurations as they do not require choker-setters to attach chokers to logs. Unhook times were significantly different between configurations based on whether or not chokers were used and whether or not they had to be unhooked manually.

Productivity varied between configurations and was heavily influenced by their associated cycle time and volume. The highest average production rate was achieved by the Falcon Shotgun configuration (46.5 m^3/PMH) but was closely followed by North Bend (46.1

m^3/PMH) and Falcon Slackline (44.3 m^3/PMH). The lowest average production rate was achieved by the North Bend Bridled configuration (32.8 m^3/PMH) but was capable at times of yarding more than 80 (m^3/PMH). Although there were differences in the predicted and observed production rates, there was considerable variability in each configuration and from cycle to cycle.

Delay analysis showed that the characteristics of how each configuration is operated and the conditions under which they were studied had an effect on both the frequency and duration of delays. Having to raise the load during inhaul in a corridor with rock bluffs proved to be the most frequent delay (0.90) for the Acme Shotgun configuration, but resulted in very little time on average (0.02 minutes). The largest delays were experienced when using the North Bend Bridled configuration which equated to a utilization rate of <73% (adjusted). This was likely because of the average length of time it took to offset haulback blocks (>20 minutes) and that the frequency (0.10).

Labor consumption was found to be lowest with the Falcon Shotgun configuration (0.07 man hours/m^3) due to only two workers being required and the high rate of production. Labor consumption was highest with the North Bend Bridled configuration (0.29 man hours/m^3) due to four or five workers being required and the associated low rate of production. The results were heavily influenced by the number of workers relative to their production rate; which is evident in the comparisons between Shotgun and Slackline configurations whether using an Acme or Falcon carriage.

Energy consumption had similar influences as labor consumption based on the associated high or low productivity of a configuration. The highest rate of energy consumption came from the North Bend Bridled configuration (25 kW/m³) despite not having a powered carriage. However, the increased kW due to the grapple carriage showed the Falcon Shotgun and Falcon Slackline configurations consumed more energy (kW/m³) despite having the highest rate of production. The lowest energy consumption rates were achieved by the Acme Shotgun configuration (7 kW/m³) due to the combination of carriage and yarder having the lowest total kW compared others, while maintaining relatively high productivity.

This study was also conducted to compare the skyline tension behavior of rigging configurations used in New Zealand. These configurations differ in maximum tensions by cycle element, average cycle tensions, payload to tension relationship, dynamic behaviors and measures of payload and tension efficiency. These differences mainly exist between unique configurations but can also differ within slight variations of the configurations.

Peak tensions during outhaul were greatest for the Falcon Shotgun and North Bend Bridled configurations; and both configurations had similar high tensions in other cycle elements. North Bend had the lowest hook peak tensions, and Falcon Shotgun had the largest due to the Skyline having to lift the load for breakout. North Bend had the lowest maximum inhaul tension, while North Bend Bridled and Acme Slackline had the largest. North Bend Bridled had the greatest peak tensions during the unhook cycle element due to the off-setting of the haulback blocks. The Falcon Shotgun and Falcon Slackline configurations had some of the lowest peak tensions during the unhook element as they lower the skyline before releasing the stems from the grapple.

North Bend Bridled had the greatest average tension per cycle operating at 81% of the safe working load, followed by Falcon shotgun which operated at 63% of the safe working load per cycle. North Bend had the lowest average cycle tension but had similarly high variability in average cycle tension like North Bend Bridled; while other configurations had very consistent average cycle tensions.

A regression equation developed to predict average cycle tension, showed that tension increased with increased payload and span but was also significantly affected by the amount of deflection. ANOVA tests indicated that there was a significant difference in average cycle tension due to configurations. The largest predicted average cycle tension was associated with the North Bend Bridled configuration, while the lowest were predicted for the Acme Slackline configuration.

A payload to tension relationship was potted for all configurations used, which showed skyline tension increased with decreasing deflection for the same carriage payload. Each configuration showed a positive trend in increased tension with increasing carriage payload, with exception to North Bend Bridled which had similar high tensions regardless of carriage payload; exhibiting an almost flat trend. The Falcon Shotgun and Falcon Slackline configurations had high variability in tensions with similar carriage payload due to variability in carriage height during inhaul from cycle to cycle.

Amplification factors of skyline pretension for breakout and maximum cyclic loads were greatest for the Falcon Slackline configuration due to tensioning the skyline before breakout and partial suspension near the landing. North Bend Bridled had the lowest breakout and cyclic load amplification factors, since little force was required with the fall block purchase during breakout and because of the extra plane of force in the skyline. Hang-ups during breakout were found to nearly double the breakout factor when extracting from a gulley with the North Bend configuration. Partial suspension of logs from the back face of a canyon with the Acme Slackline configuration was found to double the cyclic load factor, while increasing inhaul time and reducing productivity with little difference to peak inhaul tension. Normal cyclic loads during outhaul but, with high frequency loads of more than 3 Hz at tensions near the safe working load were a cause of the tension monitor coming un-clamped from the skyline, with the Falcon Shotgun configuration.

Payload and tension efficiency was calculated for each cycle of each configuration studied. Payload efficiency estimates were unusually inflated for North Bend and North Bend Bridled configuration as payload analysis programs do not accurately predict their payloads. A payload efficiency less than the tension efficiency as shown with the Falcon Shotgun configuration indicated, that production could be improved if more than one stem could be grappled for inhaul. The Acme Slackline configuration showed that partially suspending the loads improved the payload efficiency, but was a trade-off for reduced cycle time, decreased production and a higher cyclic load factor.

This study has obtained data for the comparison of rigging configurations. However, the study was limited to comparing six different configurations at eight different locations with a limited number of profiles and cycles performed. Limitations in the size and range of conditions in the data set still limit the applications of results. Regardless, the study has shown that there are differences in the productivity and skyline tension behavior of rigging configurations, despite their wide overlap in applications. The extent to which these configuration are best applied depends largely on the ability to predict overall efficiency on a cost per unit basis ($/m³).

In order to better understand the characteristics of rigging configurations, more studies need to be undertaken; not only better to estimate the efficiency of configurations in this study but also to estimate those of other configurations used in New Zealand. Additionally, the consumption rates used to determine efficiency presented in this study are limited to labor and energy. These consumption rates only provide a portion of the overall efficiency of the rigging configuration, there are many other measures including fuel efficiency which should be compared. Measuring these rates of consumption is a good way of determining whether the yarder and configuration is well adapted to the forest and terrain conditions and whether the work is being organized appropriately.

Incorporating a dedicated routine for the North Bend configuration (e.g. Woodruff 1984) into existing payload analysis software will help better plan harvests using New Zealand's most common rigging configuration. Tension monitoring of all wire ropes in a configuration, collected with GPS positional data for all components in the model (i.e. carriage & haulback blocks) could help improve the payload analysis estimates by software; such that it could be modelled and planned for in a 3D environment like ArcGIS. Alternative running line tension monitors rather than clamping tension monitors used in this study could be used to measure the tensions of the other working ropes and monitor configurations employed with running skyline systems. Additionally, yarder performance capabilities can be modeled (e.g. Willbanks 1985) and included in payload analysis software to better predict production capability. There are also many other configurations including new developments which still need to be studied and compared to aid in a better understanding of their relative efficiencies and optimal applications.

The process of collecting data and these measurements has been difficult because of the cost and time of personnel required, and the time lag in analysis, interpretation of results and putting them into practice. New and existing commercial technology like carriage mounted cameras, GPS units, fuel flow-meters, electronic measuring devices for estimating payloads and cable tension monitors, could be retrofitted into existing yarders to provide real-time feedback to operators; if data were logged and synchronized they could be used for analysis of performance and to aid in planning future operations. New technology in terms of computers and apps' are also becoming cheaper and faster in the collection and analysis of data. There is a relatively new field of "Precision Forestry," in which operational data is collected and viewed in real time, and should aid in the understanding of the application of rigging configurations. Such integrated technologies will reduce the time and effort required for traditional study methods and analysis, which in turn will speed up the feedback loop to contractors and their decision making process.

Chapter 6: Concluding Remarks on Rigging Configurations used in New Zealand

The findings of the studies presented in this thesis showed that different cable logging systems and individual rigging configurations have optimal applications given stand and terrain conditions.

A comprehensive literature review (Chapter 2), highlighted that many research projects have studied the various aspects of cable logging operations and that many concepts and ideas of current interest to New Zealand have been approached before. Recent research world-wide has investigated efficiency of logging machinery and operations, and improvements made through adopting new technologies. However, the literature review showed despite many manuals and best practice guidelines, there was little information relating to which rigging configurations are more productive or safer under various stand and terrain conditions. In this respect the survey of practitioners and operational production studies in this thesis provides new information. New Zealand is in a unique position given current needs, innovation and research capacity to become world leaders in these efforts in regards to cable logging.

An industry survey in Chapter 3 showed there are wide overlaps in the physical capabilities of rigging configurations, which make it difficult to choose which one to employ. The survey also highlighted a reliance on several configurations, hesitance to adopt or try other configurations and mixed perceptions about the relative advantages and disadvantages of each. An expert panel used the Delphi process to arrive at a consensus about the true advantages and disadvantages of each rigging configuration to provide clarity, and discussed trade-offs between configurations in terms of operating characteristics.

The survey of practitioners showed that in 2011 there was little use, and limited knowledge, of higher productivity rigging configurations such as motorized carriages and mechanical grapples. Survey results also indicated that the rigging configurations of South Bend and Block in the Bight were rarely used, even though they were very similar variations of the most often used configuration, North Bend. The reasons toward favoring North Bend were various but mostly due to crew experience, lack of exposure, and concerns over increased wire rope wear and tensions.

In Chapter 4 a model yarder was used to compare the dynamic tensions of the North Bend, South Bend, and Block in the Bight configurations, due to known causes of shock loading (i.e. drops into full suspension, impacts with ground objects, and breakout forces when bridling). Results showed that there were differences between tensions of the three rigging configurations, and some performed better than others in given shock loading tests. Recommendations were provided on ways that logging practitioners can minimize dynamic tensions, specifically by using North Bend in situations where loads could suddenly change from partial to full suspension (i.e. drop); using South Bend in situations where there is a high risk of impact with ground objects during inhaul; and avoiding the use of long chokers when bridling, especially when using the Block in the Bight configuration.

Chapter 5 compared dynamic skyline tension behavior of various rigging configurations, as well as their productivity, by way of a series of targeted field studies. Results showed that average productivity ranged from 32.8 (m^3/PMH) for North Bend Bridled to 46.5 (m^3/PMH) for Falcon Shotgun. However, older configurations like North Bend achieved similar average productivity (46.1 m^3/PMH). However, the Falcon Shotgun configuration had the capacity to produce more than 100 (m^3/PMH), while North Bend had the capacity to reach more than 70 (m^3/PMH).Skyline tensions were recorded for 259 cycles of which 137 cycles (53%) exceeded the safe working load, which occurred at seven of the eight study sites and across 14 of the 16 profiles. Average cycle tensions were greatest for North Bend Bridled configuration, operating at 81% of the safe working load which was nearly double the average cycle tension for North Bend and produced similar tensions during all elements of the yarding cycle; most likely a result of the off-setting of the haulback blocks creating an extra plane of force acting on the skyline. The Falcon Shotgun configuration produced the greatest peak tensions during the outhaul component of the yarding cycle and had high variability in tensions during inhaul, due to the weight of the carriage and inconsistency of skyline lifts. Amplification factors for the breakout of stems at the start of the inhaul element of yarding cycles were greatest for the Falcon Shotgun and Falcon Slackline configurations with most between a factor of two and 12 times the static skyline pretension; while all other configurations were less than a factor of two. Cyclic load amplifications were also greater for the Falcon Shotgun and Slackline configurations with most between one and five times the skyline pretention; while most other configurations were less than a factor of one. The relationship between payload and tension was investigated, and indicated that all configurations have reduced skyline tensions with either smaller payloads or increased deflection. The standing skyline configurations behaved similar, with exception to North Bend Bridled; where tensions were equally high for small and large payloads. The study also showed that production information could be used to compute measures of labor and energy consumption; which provided insight into operational performance, and could be used in conjunction with cost data to derive further measures of operational efficiency. Labor consumption greatest with the North Bend Bridled configuration (0.29 man hours/m^3), while the Falcon Shotgun configuration had the lowest rate (0.07 man hours/m^3). Energy consumption was also the greatest for North Bend Bridled (25 kW/m^3) due to the low associated productivity and the powerful 335 kW engine with the yarders used; in contrast to North Bend which had greater productivity and only consumed 9 kW/m^3. The least energy consuming configuration was Acme Shotgun (7 kW/m^3); while Falcon Shotgun and Falcon Slackline had high productivity the combined power of the yarder and carriage resulted in greater energy consumption (15 and 17 kW/m^3, respectively). The study also showed that tensions could be collected to compute measures of payload and tension efficiency, which also provided insight into operational performance. Payload efficiency was greatest for North Bend Bridled Study Site Six (factor >2,500), North Bend Study Site Three (factor >2.5) and Acme Slackline Study Site Four (factor >2). The North Bend Bridled and North Bend may be misleading as payload analysis software does not have a dedicated analysis for these configurations and does not account for the skyline sharing the payload with main and haulback, as well as their geometry with regards to the fall block. For example, Study Site Six had a 3.8 % deflection and a blind lead area where no payload capability was predicted by software, but North Bend Bridled was still effective but was essentially Highleading at the cost of excessive skyline tensions. In contrast, the Acme Slackline configuration studied partially suspended many of their payloads while software did not; despite this practice proving to be less productive and result in greater cyclic load amplifications. Tension efficiency was also greatest with the North Bend Bridled configuration (factor >0.80) but this also posed a concern as 95% of cycles exceeded the safe working load for most of the cycle and peak tensions reached 42% breaking strength. Tension efficiency was lowest with the

North Bend configuration at Study Site Seven; where good deflection in one span allowed for larger payloads; but this also highlights software inability accurately predict skyline tensions for this configuration. A payload efficiency less than the tension efficiency as shown with the Falcon Shotgun configuration indicated, that production could be improved if more than one stem could be grappled for inhaul.

The operational production studies in this thesis have added to the understanding of the dynamic forces during cable logging and have determined that static and dynamic forces differ between rigging configurations. The frequency of exceeding the safe working load 53% of all cycles studied and occurred at seven of eight study sites. Therefore, the conclusion can be drawn that the peak dynamic tensions often approach the endurance limit of the skylines (50% breaking strength) and skyline wear or risk of failure is therefore higher than it would be if peak dynamic tensions were reduced. Operations studied which did not have their own tension monitor with display for the yarder operator, exceeded the safe working load at a frequency of 74 to 95%; while those who used tension monitors exceeded the safe working load at a frequency of zero to 65%. In order to increase awareness of skyline tensions exceeding the safe working load and to better manage peak dynamic tensions in cable logging operations it is recommended that the industry give serious consideration to installing tension monitors in all cable yarding machines in New Zealand.

Further research into understanding rigging configurations used in New Zealand cable logging operations is of interest to the forest industry and the country to remain competitive with other nations. More comparative production studies should be performed in the coming years to help determine the optimal applications of rigging configurations. The high costs of cable logging on steep terrain may be countered by the increase in crew efficiency and safety when the work is better planned for and organized, techniques are improved and new technologies applied. In simple terms, “there is always room for improvement.”

The improvements in cable logging will not come easy, but the future of the industry will depend on them to accomplish the step-change into greater proportions of steep terrain logging. However, at the present time innovation is alive and well within New Zealand’s forest industry; and the future looks bright.

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Appendix:

What Rigging Configuration is Best? Interview Guide...

Goal: Improve understanding of rigging configurations and its optimum application in timber harvesting

R. Visser, H. Harrill

– University of Canterbury

Name: ____________________ ☐ Anonymous   Company/Region: ______________________   Circle: Yarder Operator / Planner / Owner(Foreman)

Yarder (make and model):__________________________________

Carriage(s):_________________________________

What rigging configuration do you use most often?_______________________

What other configurations have you used in the last 5 years?___________________________

____

What type of carriages do you have? _______________________________________

____

If you are familiar with the following, what are the advantages and or disadvantages:

	U	F	D	Advantage?	Disadvantage?
Highlead					
Running skyline (scab)					
North Bend					

South Bend					
Live skyline					
Motorized carriage					
Mechanical Carriage					
Dutchman (side-block)					
Radio-controlled chokers					
Mobile tailhold					

240

Grapple					

If you have an opinion, what rigging configuration would you suggest works best given the following (If need be, assume Tower Yarder 1 1/8th (28mm) skyline?)

1. Distance out: (enter distances that you consider to differentiate 'short' from 'long')

   Less than ___m? ______________________________

   Greater than ___m? ______________________________

2. Extraction Direction:

   Uphill, ______________________________

   Downhill ______________________________

3. Very steep chord slope (top of tower down to tailhold)

   ____

   ____

4. Deflection:

   Low (<6%)______________________________

   Medium (>6%, <15%) ______________________________

   High (>15%)______________________________

   really high (>25%(14°), i.e. deep gulley / full suspension)______________________________

5. Broken Terrain: i.e. rough terrain with incised gulley's

   ____

   ____

6. Ability to fly logs over an SMZ

7. Ability to pull away from native bush boundary

8. Landing size, space in front of yarder:

   Plenty ____

   Limited space ____

9. Yarder type: Swing yarder (note repeat above questions for Swing Yarder if they are familiar with it)